ARCADIS
Infrastructure · Water · Environment · Buildings

Imagine the result

Coastal Green Infrastructure Research Plan for New York City

December 8, 2014

ARCADIS

New England Interstate Water Pollution Control Commission (NEIWPCC)

New York State Department of Environmental Conservation (NYSDEC) Hudson River Estuary Program

NYC PLANNING
DEPARTMENT OF CITY PLANNING CITY OF NEW YORK

ARCADIS

Contributing Authors

ARCADIS

Haihong Zhao
Hugh Roberts
Jessica Ludy

Stevens Institute of Technology

Andrew Rella
Jon Miller
Philip Orton

The Nature Conservancy

George Schuler
Lauren Alleman
Andrew Peck
Rebecca Shirer

NYC Parks

Jamie Ong
Marit Larson

Mathews Nielsen Landscape Architects

Kim Mathews

SCAPE Landscape

Kate Orff
Gena Wirth
Lauren Elachi

Table of Contents

Contributing Authors		**i**
Executive Summary		**i**
1.	**Introduction**	**1**
1.1.	Motivation	1
1.2.	Research Priorities	2
1.3.	Workshops	3
1.4.	Document Format	5
2.	**Regulatory Considerations**	**7**
3.	**Literature Review**	**11**
3.1.	Constructed Wetlands and Maritime Forests	14
3.1.1.	Strategy Description	14
3.1.2.	An Update on the Status of the Science	16
3.1.3.	Unknowns and Data Gaps	25
3.2.	Constructed Reefs	27
3.2.1.	Strategy Description	27
3.2.2.	An Update on the Status of the Science	29
3.2.3.	Unknowns and Data Gaps	33
3.3.	Constructed Breakwater Islands	34
3.3.1.	Strategy Description	34
3.3.2.	An Update on the Status of the Science	36
3.3.3.	Unknowns and Data Gaps	39
3.4.	Channel Shallowing	40
3.4.1.	Strategy Description	40
3.4.2.	An Update on the Status of the Science	41
3.4.3.	Unknowns and Data Gaps	43
3.5.	Ecologically-Enhanced Bulkheads and Revetments	44
3.5.1.	Strategy Description	44

3.5.2. An Update on the Status of the Science 47

3.5.3. Unknowns and Data Gaps 50

3.6. Living Shorelines 50

3.6.1. Strategy Description 50

3.6.2. An Update on the Status of the Science 52

3.6.3. Unknowns and Data Gaps 54

4. Data, Conceptual Models, Monitoring, and Integration 55

4.1. Baseline Data 55

4.2. Conceptual Models 65

4.3. Monitoring 67

4.4. Integration 68

5. Meta-strategy Research Plan 71

Agenda 5.1 Conceptual Models and Monitoring Protocols Development 72

Agenda 5.2 Development of Rapid Assessment Tools and Ecosystem Models 77

Agenda 5.3 Sediment study 81

Agenda 5.4 Ice Study 84

Agenda 5.5 Vessel Wake Assessment 87

Agenda 5.6 Cross-Agency Data and Metadata Management 89

Agenda 5.7 Comparison of Marsh Species – Phragmites and Spartina 91

Agenda 5.8 Pilot Project Identification, Implementation, and Monitoring (Living Laboratory) 94

Agenda 5.9 Evaluation of the Regulatory Process 96

Agenda 5.10 Shoreline assessment for appropriateness of CGI Strategy 98

Agenda 5.11 Coastal Resiliency Benefits Quantification of Wave and Current Velocity Reduction 100

6. Strategic Research Plan 102

6.1. Constructed Wetland Research Agendas 102

Agenda 6.1.1 Vegetative Flow Resistance and Storm Wave Attenuation Potential of Salt Marsh and Maritime Forest 102

Agenda 6.1.2 Resiliency of Maritime Forests and Coastal Wetlands under a Natural, Healthy Condition and Impacts of Urban Nature 105

6.2. Reef Research Agendas 107

Agenda 6.2.1 Complex Flow and Wave Transmission Analysis of Constructed Reefs 107

Agenda 6.2.2 Oyster Habitat Assessment 109

6.3. Channel Shallowing Research Agendas 111

Agenda 6.3.1 General Research on of the Effects and Feasibility of Channel Shallowing for Flood Risk Reduction in NYC 111

Agenda 6.3.1 General Research on of the Effects and Feasibility of Channel Shallowing for Flood Risk Reduction in NYC 112

Agenda 6.3.2 Environmental Study of the Channel Shallowing Strategy at a Feasible Location Motivation 113

6.4. Ecologically-enhanced Bulkheads and Revetments Research Agendas 115

Agenda 6.4.1 Ecologically-enhanced Bulkheads and Revetments Design Guidelines 115

Agenda 6.4.2 Structural Benefits of Marine Growth on Marine Infrastructure 117

6.5. Living Shorelines Research Agendas 119

Agenda 6.5.1 Living Shoreline Design Guidelines 119

7. Research Summary 122

8. Literature Cited 128

Tables

Table 1. Benefits of CGI strategies in hazard mitigation and ecological enhancement 12

Table 2. CGI strategy performance metrics 13

Table 3. Impacts of the wetland and maritime forest properties on vegetative resistance 17

Table 4. Characteristics of ecological enhancement hazard mitigation measures 46

Table 5. Environmental data inventory and metrics 57

Table 6. Ecological data inventory and metrics 59

Table 7. Potential project monitoring locations 65

Figures

Figure 1.	Wetland location within the watershed (Kusler 1983)	14
Figure 2.	Diagram of constructed wetlands (NYC DCP 2013), wetland marshes (NYSDEC 2013), and maritime forest (Photographed by John W. McCord in Whitaker et al. 2009)	14
Figure 3.	Diagram of constructed reefs (NYC DCP 2013) and photo of living reefs (Katlin Walling)	28
Figure 4.	Conceptual view of a constructed breakwater island in the Fort Pierce Marina, Florida (Czlapinski 2013)	35
Figure 5.	Diagram of channel shallowing (NYC DCP 2013)	40
Figure 6.	Photograph of an ecologically-enhanced bulkhead at Hunts Point Landing, Bronx, NY (HDR Engineering, Inc.) and sketches of other possible ecological enhancements.	44
Figure 7.	A sketch of living shorelines (CBF 2007)	51
Figure 8.	Geomorphology category	56
Figure 9.	Observation stations	60
Figure 10.	Illustration of bottom sediment sampling coverage. Left: usSEABED database (Reid et al. 2005) and HRE Sediment Map (Bell et al. 2005); right: USEPA sediment quality study (Adams and Benyi 2003)	62

ARCADIS	ARCADIS U.S., Inc.
BACI	Before-After-Control-Impact
BCA	Benefit Cost Analysis
CBI	Consensus Building Institute
CCAP	Coastal Change Analysis Program
CDOM	Colored Dissolved Organic Matter
CGI	Coastal Green Infrastructure
CO-OPS	Center for Operational Oceanographic Products and Services
CRMS	Coastwide Reference Monitoring System
CRP	Comprehensive Restoration Plan
CRT	Coastal Resilience Tool
CWPPRA	The Coastal Wetlands Planning, Protection, and Restoration Act
DISL	Dauphin Island Sea Lab
DO	Dissolved Oxygen
DRERIP	Delta Regional Ecosystem Restoration Implementation Plan
EwE	Ecopath with Ecosim
FEMA	Federal Emergency Management Agency
GAP	Gap Analysis Program
GHG	Greenhouse Gas
GIS	Geographic information System
H*WIND	HRD Real-time Hurricane Wind Analysis System
HEP	Hudson River Estuary Program
HRD	Hurricane Research Division
HRE	Hudson River Estuary
HRECOS	Hudson River Environmental Conditions Observing System
HRF	Hudson River Foundation
HRNERR	Hudson River National Estuarine Research Reserve
HRV	Hudson River Valley
IEC	Interstate Environmental Commission
LULC	Land Use/Land Cover
LUMCON	Louisiana Universities Marine Consortium

MEM	Marsh Equilibrium Model
NACCS	North Atlantic Coast Comprehensive Study
NDBC	National Data Buoy Center
NEIWPCC	New England Interstate Water Pollution Control
NG-CHC	Northern Gulf Coastal Hazards Collaboratory
NGDC	National Geophysical Data Center
NJ	New Jersey
NJDEP	New Jersey Department of Environmental Protection
NLCD	National Land Cover Database
NOAA	National Oceanic and Atmospheric Administration
NOS	National Ocean Service
NPS	National Park Service
NWRs	National Wildlife Refuges
NY	New York
NY Rising	The New York Rising Community Reconstruction Program
NY/NJ	New York-New Jersey
NYC	New York City
NYCDCP	New York City Department of City Planning
NYCDEP	New York City Department of Environmental Protection
NYCDPR	New York City Department of Parks & Recreation
NYCEDC	New York City Economic Development Corporation
NYCRR	New York Codes, Rules and Regulations
NYDOS	New York Department of State
NY-GAP	New York Gap Analysis Project
NYHOPS	New York Harbor Observing and Prediction System
NYS	New York State
NYSDEC	New York State Department of Environmental Conservation
ORRP	Oyster Restoration Research Project
RCC	Reef Check California
SAP	Standard Activity Permit
SAV	submerged aquatic vegetation

SIRR	Special Initiative for Rebuilding and Resiliency
SLAMM	Sea Level Affecting Marshes Model
SRI@JB	Science and Resilience Institute at Jamaica Bay
SST	Sea Surface Temperature
TEC	Target Ecosystem Characteristics
TNC	The Nature Conservancy
USACE	US Army Corps of Engineers
USEPA	U.S. Environmental Protection Agency
US-ERDC	U.S. Army Engineer Research and Development Center
WAVCIS	Louisiana State University Wave-Current-surge Information System

Executive Summary

ARCADIS U.S., Inc., has partnered with the Stevens Institute of Technology and has been supported by The Nature Conservancy, the New York City Department of Parks & Recreation, Mathews Nielsen Landscape Architects, and SCAPE Landscape Architecture to conduct the principal research on coastal green infrastructure (CGI) strategies. Available literature has been reviewed to determine the status of the science related to these strategies, including unknowns and data gaps related to each strategy, in order to develop a research agenda to guide future in-depth studies that will:

- Advance the understanding of the benefits and impacts of CGI strategies;
- Mitigate coastal hazards; and
- Enhance ecological services.

The goal is to deliver a research agenda that will advance an understanding of the benefits and costs of CGI strategies, to ultimately facilitate the selection and implementation of projects which can most successfully improve resiliency in the New York City (NYC) coastal environment.

CGI strategies are defined as those that create, restore, or emulate natural coastal features as well as provide the potential benefits of reducing erosion and mitigating storm surge, wave action, and still-water flooding associated with coastal flood events. Six CGI strategies that are potentially applicable to NYC coastal areas were the focus of this research. The selected strategies include:

- Constructed wetlands and maritime forests;
- Constructed reefs;
- Constructed breakwater islands;
- Channel shallowing;
- Ecologically-enhanced bulkheads and revetments; and
- Living shorelines (sill-type).

Each CGI strategy was thoroughly reviewed from the aspects of hazard mitigation potential, ecological benefits, and failure drivers, from which unknowns and data gaps were identified. In parallel, preliminary investigations were conducted related to existing regulations for CGI projects, data collection and dissemination, and conceptual models that would synchronize science, data, and policy. Building upon the review of data gaps and unknowns in the literature, research agendas and tasks have been developed to improve our understanding of CGI strategies. Three workshops were held as part of this study. The first was a kickoff meeting held in December 2013 to introduce stakeholders to the project, and discuss the context and scope. The second was held in April 2014, focusing on regulatory considerations. The third in October 2014 included over 40 participants from 21 agencies, companies and institutions to discuss improvements and additions to the draft research plan. All workshops included participation of scientists, engineers,

managers, and regulators. Diverse and constructive comments were received, aiding in the refinement and development of the research plan.

The research plan consists of two agenda groupings: meta-strategy agendas and strategy-specific agendas. The meta-strategy research agendas include tasks that will benefit all CGI strategies in NYC. The strategy-specific research agendas target individual CGI strategies with the goal of clarifying how CGI strategies best provide hazard mitigation and improved habitat values. For each research agenda, one or multiple sub-tasks are designed for clarifying the desired outcomes and qualified personnel.

In the meta-strategy agendas, eleven research topics are described, including 1) cross-science topics like the development of conceptual models and CGI strategy prioritization for shoreline reaches, 2) cross-agency topics like the development of data and metadata sharing platforms and implementation and monitoring of pilot projects, 3) baseline science and data improvement topics like consistent monitoring protocols and sediment, ice, and vessel wake studies, and 4) topics which can support the regulatory review process such as the development of rapid project assessment tools. Many of these research agendas would be most successful with cross-agency coordination and diverse funding sources.

The strategy-specific research topics are identified as the top priorities for understanding each CGI strategy and promoting effective implementation. For instance, the understanding of vegetation-induced flow resistance can be advanced to better quantify the hazard mitigation potential (e.g., wave attenuation) of a constructed wetland and other CGI strategies. Additionally, the design and implementation of ecologically-enhanced bulkheads and revetments, as well as living shorelines, can be improved by developing design guidelines.

The research agendas in this report aim to lay the foundation for the coordination of future research items in the New York City area based on the current status of the science. As research items are addressed and new demands and questions emerge, this research plan should be modified to focus coordination and collaboration related to the advancement of CGI strategies. In the near term, this research agenda will be most impactful if the research agenda items stimulate collaboration amongst agencies, institutions and other stakeholders to prioritize items, including the research agendas described, to cooperatively advance the science of CGI strategies.

1. Introduction

ARCADIS U.S., Inc. (ARCADIS) partnered with the Stevens Institute of Technology and was supported by The Nature Conservancy (TNC), the New York City Department of Parks & Recreation (NYCDPR), Mathews Nielsen Landscape Architects, and SCAPE Landscape Architecture to conduct a literature review of Coastal Green Infrastructure (CGI) strategies intended to reduce coastal flood risks and enhance ecological services. The goal is to deliver a research agenda for guiding future in-depth studies that will advance an understanding of the benefits and costs of CGI strategies, to ultimately facilitate the selection and implementation of projects which can most successfully improve resiliency in the New York City (NYC) coastal environment. For the purposes of this study, CGI strategies are defined as those that create, restore, or emulate natural coastal features, as well as provide the potential benefits of reducing erosion and mitigating storm surge, wave action, and stillwater flooding associated with coastal flood events. These strategies are often referred to as living shorelines, ecological engineering, or natural and nature-based features (Mitsch and Jørgensen 2004; DNRMD 2014; Guise 2014).

1.1. Motivation

The New York State Department of Environmental Conservation (NYSDEC) Hudson River Estuary (HRE) Program Action Agenda outlines specific goals and targets related to helping communities adapt to sea-level rise and severe storms. One objective is to develop guidance for local governments on shoreline adaptation strategies to respond to shoreline inundation along the estuary and its tributaries from the Troy Dam south to the Verrazano Narrows. Another objective is to identify management techniques and measures that promote sustainable shorelines and develop and disseminate guidance on shoreline protection options to respond to sea-level rise. The Estuary Program boundaries end at the Verrazano Narrows; however, large-scale solutions to increase resilience to flooding in NYC would likely affect the entire estuary ecosystem. For this reason, the Estuary Program is supporting an evaluation of CGI strategies that would be appropriate for all of NYC. The New England Interstate Water Pollution Control Commission (NEIWPCC) strives to coordinate activities and forums that encourage cooperation among the states, educate the public about key water quality issues, support research projects, train environmental professionals, and provide overall leadership in the management and protection of water quality. Through a partnership with NYSDEC, NEIWPCC supports the HRE Program by providing technical assistance and program support.

Over the course of decades, efforts have been made in NYC to establish policies for development and use of the waterfront and to provide the framework for evaluating the consistency of all discretionary actions in the coastal zone (New York City Department of City Planning [NYC DCP] 1982; NYC DCP 2002; The City of New York 2011; NYC DCP 2011; MWA 2014). Triggered by Hurricane Sandy (2012), the NYC Special Initiative for Rebuilding and Resiliency (SIRR) and the North Atlantic Coast Comprehensive Study (NACCS; USACE 2014) were initiated in succession. The former analyzed the impacts of extreme events and long-term changes in climate on infrastructure, buildings, and the economy over the medium term (2020s) and long term (2050s). It is stated that a “resilient” city is defined as one that is “able to bounce back after change or adversity” and “is capable of preparing for and responding to difficult conditions” (The City of New York 2013). The NACCS was targeted toward reducing flood risk to vulnerable coastal populations and promoting resiliency of coastal communities to ensure a sustainable and robust coastal landscape system, considering future sea-level rise and climate change scenarios.

Given the uncertainties in future coastal hazards, a more sustainable and adaptable solution is required to protect shoreline areas. Natural wetlands, barrier islands, and shorelines should be conserved wherever possible for their hazard mitigation and obvious ecological benefits. Unfortunately, their extent has been dramatically reduced over time due to development, dredging, and other human impacts. Most of the existing traditional coastal hazard mitigation measures, such as bulkheads, seawalls, revetments, and riprap, often lack adaptability and can have detrimental ecological effects including water quality degradation, sediment starvation, shallow water habitat damage, and/or waterfront access limitations. Due to the vast stretches of existing infrastructure on the coastline, identifying ways to build and retrofit shoreline mitigation measures will be critical to improving the City’s resiliency against coastal hazards while preserving the economic, social, and ecological well-being of the region. With the role of the ecosystem in protecting waterfront communities from coastal hazards becoming more recognized (e.g., Barbier et al. 2013), CGI strategies are becoming more widely used on coastlines around the United States and internationally (Swann 2008; De Vriend and Van Koningsveld 2012; Bridges et al. 2013; TNC 2013). Planning efforts over the last 30 years by multiple agencies in NYC, including the DCP, demonstrates the local aspiration to advance the integration of CGI strategies in its coastal protection. However, there are many unknowns related to CGI strategies’ potential to mitigate coastal hazards and enhance ecological services. Improving the understanding of these strategies can advance project design and streamline implementation, evaluation, long-term operations, and maintenance.

1.2. Research Priorities

In order to improve the design and implementation of CGI strategies, it is critical to first improve the understanding of these strategies’ ecosystem goods and services and hazard mitigation potential. CGI strategies are often intended to mitigate event-based hazards and gradual hazards. Event-based hazards happen during an acute event, such as storms, according to the Urban Waterfront Adaptive Strategies study (NYC DCP 2013). These hazards include storm surge induced flooding, wave forces, and sudden erosion. Gradual hazards, on the other hand, affect coastal communities chronically, such as gradual erosion due to daily marine forces and frequent and extended flooding during high tides worsened by continued sea-level rise. The NYC Panel on Climate Change projects that sea levels in NYC will rise between 8 and 30 inches by the 2050s and between 15 and 75 inches by 2100 (NPCC 2014). CGI strategies to mitigate the risks posed to the shoreline under both current and future sea-level rise scenarios will need to be tailored to the specific nature of the shoreline vulnerability itself.

CGI strategies are innovative measures, which often challenge the traditional regulatory process, require extensive data collection and advanced scientific assessments. Data gaps, unknowns, and implementation challenges, including existing regulatory considerations, were identified through literature review, team discussions, expert interviews, and workshops. High-priority research topics were recommended on the basis of gaps and questions identified during the literature review, as well as through discussions with stakeholders and workshops.

In the present study, six types of CGI strategies with the highest priority for NYSDEC and NYC DCP were selected from the list of potential adaptive strategies in the Urban Waterfront Adaptive Strategies study (NYC DCP 2013) to be further analyzed. These strategies are listed below. A brief definition is added here for an overview. More detailed definitions are provided in Section 3, Literature Review, for each individual strategy type.

- **Constructed wetlands and upland maritime forests** are new or restored coastal wetlands that lie in sheltered and low elevation areas from mean tide level to spring high tide and forest that develop above the spring high tide level. Upland maritime forests are new or restored forests that can tolerate high salinity and sandy soils at an elevation above the spring high tide level.
- **Constructed reefs** are artificially made reefs that are emergent, near-emergent or fully submerged and are designed for a variety of goals including wave attenuation, fish habitat, oyster restoration, recreational diving, protection of endangered habitats, and others.
- **Constructed breakwater islands** are artificial islands that mimic sand bars, wetland islands, or structured rocky habitat and protect oceanfront areas from wave action.
- **Channel shallowing** is a strategy of reducing estuary or inlet depths to reduce the inland penetration of storm tides and can be a form of restoration in dredged systems that were historically shallower.
- **Ecologically-enhanced bulkheads and revetments** are hardened shore armoring structures with ecological elements.
- **Living shorelines**, specifically sill-type for this study, are soft shore stabilization treatments that require sediment fill, sill, and planting.

The research plan is intended to be a living document and can be updated as new information is obtained, information is developed, and information gaps are filled. Given the multiple interests, agencies, and stakeholders, this research plan can serve as a platform for collaboration and to encourage interagency communication and coordination toward similar goals.

1.3. Workshops

As part of this study, three workshops were held to discuss regulatory challenges and recommended research topics. In all workshops, participants included scientists, engineers, managers, and regulators. The kickoff meeting held on December 9, 2013 introduced stakeholders to the project, presented an overview of related initiatives in the region, and generated initial discussion about priorities and goals. The workshop held on April 25, 2014 was devoted to discussion of the existing regulatory framework, which raised a variety of concerns and challenges including but not limited to required data categories, existing data gaps, baseline data collection, project impacts and benefits evaluation, pilot project scales and existing permitting processes. Overall, the discussion emphasized the importance of this study and the close relationship between this research plan and regulation of CGI projects. Critical components of future studies, such as pilot project identification and prioritization, development of monitoring protocol, development of habitat evaluation models and regulatory evolution were brought forward and became some of the research recommendations in this study.

The second in October 2014 concentrated on improving the identified research agendas. Over 40 participants from 19 agencies, companies and institutions attended to discuss improvements and additions to the draft research plan. Organizations that attended the workshop are listed alphabetically as follows:

- ARCADIS U.S., Inc.
- Consensus Building Institute
- Environmental Defense Fund
- Environmental Protection Agency, Region 2
- Hudson River Foundation
- Interstate Environmental Commission
- Mathews Nielsen Landscape Architecture
- New York City Department of City Planning
- New York City Department of Parks & Recreation

- New York City Economic Development Corporation
- New York State Department of State
- New York State Department of Environmental Conservation
- Ocean & Coastal Consultants
- Port Authority of New York and New Jersey
- Princeton University
- SCAPE/Landscape Architecture
- Stevens Institute of Technology
- The Natural Conservancy
- US Army Corps of Engineers, New York District

Discussion in the workshop was guided by a pre-meeting survey that prioritized the research topics per the preferences of invited individuals. Management-level and data collecting research agendas were the highest ranked meta-strategy agendas. Improving the understanding of hazard mitigation potential due to vegetation and corresponding shoreline resiliency was the highest priority strategy specific agenda item. The research agendas in the final report are influenced by the discussion in both workshops. Meeting minutes are available for each workshop.

1.4. Document Format

The subsequent sections of the document are as follows.

Section 2 (Regulatory Considerations) provides overall comments and recommendations on regulation and permitting for innovative CGI strategies. The focus is the need for improved scientific understanding of selected strategies to facilitate the consistency and efficiency of permitting.

Section 3 (Literature Review) documents the status of the science, data gaps, unknowns, and research direction for each strategy.

Section 4 (Data, Monitoring, and Integration) describes the current state of observation data availability, data scarcity in time and space, and a potential data sharing and information transferring platform; recommends the development of conceptual models and cross-table monitoring protocol; and indicates a path forward.

Section 5 (Meta-strategy Research Plan) describes the goals, objectives, research approaches, and expected contributions for research tasks that will benefit multiple CGI strategies in NYC.

Section 6 (Strategic Research Plan) describes CGI strategy-specific research goals, objectives, research approaches, and expected contributions.

Section 7 includes a table that ranks all research agenda items according to four criteria: Fundamental Principles, Chronology, Regional Applicability, and Affordability. Detailed supporting information is provided in Sections 5 and 6.

Section 8 lists literature cited in the text.

2. Regulatory Considerations

Because CGI strategies have the potential to impact local ecosystems and adjacent waterfront property, most of the CGI strategies discussed in this report will be subject to the same regulatory and permitting processes as traditional shoreline armoring infrastructure and waterfront development. As such, many of the strategies discussed in this report could be incompatible with the current enabling legislation and regulations and will therefore be challenging to implement. For example, Title 6, New York Codes, Rules and Regulations, Section 661 (6 NYCRR §661) contains specific language restricting the placement of "fill" in waterways, which would effectively prohibit most of the CGI strategies discussed in this report. Other regulatory challenges include personnel limitations; unknowns related to costs and benefits of CGI including uncertainty associated with the performance of a given strategy in a certain location; potential impacts (positive or negative) on the surrounding ecosystems; public health concerns; and social concerns. This section will briefly discuss the current framework of the permitting process, limitations of the permitting process, and some regulators' concerns. Lastly, this section will recommend areas of further research to address the concerns.

The legislation relevant to CGI mostly relates to the regulation of tidal wetlands (6 NYCRR §661, Article 25 of Environmental Conservation law) and was put in place in order to avoid or mitigate the negative impacts of human-made construction on tidal wetlands with a strong emphasis on limiting actions that are not "what is reasonable and necessary" (6 NYCRR §661.9). According to the legislation, a project "must not endanger the health, safety or welfare of the people of the state of New York, and must not cause unreasonable, uncontrolled or unnecessary damage to the natural resources of the state, including soil, forests, water fish, shellfish, crustaceans and the aquatic and land-related environment." Further, projects must maximize aquatic habitat in all possible settings, even those challenged by urban development. Additional regulations and permitting requirements governing coastal infrastructure are those of the Clean Water Act (concerning 404 permits), the state's Coastal Zone Management Program, which is administered by the New York Department of State (NYDOS), and the NYC Waterfront Revitalization Program, administered by the NYC DCP.

The inherent challenge of restoring aquatic ecosystems and implementing CGI within the existing regulatory framework can be illustrated with salt marsh, which, in NYC, typically occurs in a narrow fringe between developed infrastructure and mudflats or open water. Many of the ecosystem services defined for wetland systems are dependent on wetland size. Because salt marsh areas are significantly limited in NYC where open space is relatively scarce and land is valued at a premium, placing fill in mudflats could be a way to restore some salt marshes to an appropriate size without taking too much land away from development. However, replacing mudflat habitat with another habitat type is difficult to permit under the enabling legislation. A thorough habitat tradeoff analysis is needed to evaluate mudflat habitat values versus converted salt marsh habitat values. Having this type of study up-front can provide guidance to conditionally permit salt marsh construction from mudflats. Subordinate clauses may include size of residual mudflats, ratio of water area to marsh area, abundance of key fish species, wave reduction potential, etc.

More frequent implementation of CGI in NYC and the State may ultimately require changes to regulatory processes that can streamline CGI permitting. Research by the Georgetown Climate Center (2013) showed that most standard U.S. Army Corps of Engineers (USACE) permitting favors a “hard” engineering approach to shorelines. However, in precedents from Alabama and Maryland, states have worked with the USACE to encourage CGI strategies, through Programmatic General Permits and Regional General Permits, as well as offering to provide additional technical guidance on design, construction, and evaluation of CGI. Similarly, CGI strategies in Virginia and Rhode Island are more widely applied than elsewhere, in part due to changes in governing legislation. While these specific permits may not be applicable in NYC and New York State, a similar process toward streamlining CGI permitting could be proposed to justify a framework for a potentially simpler and quicker decision. For example, where results of pilot studies could demonstrate that certain types of CGI projects provide improved ecosystem services, it may be possible to acquire a Standard Activity Permit (SAP), which is similar to the USACE Nationwide General Permit. Permitting CGI using a SAP would have the added benefit of relieving some of the regulatory burden on limited personnel by simplifying the approval of CGI beforehand. Future research should explore where there is opportunity or flexibility in the existing regulatory framework to enable implementation of CGI and to identify what would be required to make CGI projects eligible for a SAP.

Another concern is that there is currently no agreement among agencies on conservation goals, priority species, and habitats (especially benthic habitat) for NYC, which makes decision making and permitting difficult. Achieving consensus on key habitat, species, and indicators requires more detailed benthic and habitat data and focused discussion. Additional challenges associated with permitting include personnel limitations and capacity of the agencies to process permits. In Long Island, for example, as few as three or four people are responsible for reviewing 1,000 to 2,000 permit applications per year. Given that CGI projects are non-traditional, the extra time required could be a deterrent for permitting these types of projects. Up-front studies and development of a database with metadata of all implemented, permitted, and proposed projects will help avoid redundant research and overview and thus speed up the permitting process.

There are a number of other concerns with CGI that regulators must address when permitting coastal infrastructure projects. One is tied to the uncertainty associated with both ecosystem and coastal hazard reduction performance. As CGI progresses, regulators need to know which strategies work well in which locations and what hazards they aim to address. If wave attenuation or fish habitat is desired, for example, what would be the appropriate CGI strategy? Some of this work has been started for the Hudson estuary as part of the Hudson River National Estuarine Research Reserve (HRNERR) Sustainable Shorelines project. Due to the historical loss of aquatic habitat, in particular submerged aquatic vegetation (SAV), there is a strong drive and emphasis in the region to preserve and restore aquatic habitat. Therefore, an important question of any shoreline infrastructure project is how it will affect or replace the existing habitat. Implementing CGI may, for example, in some cases replace SAV with other types of vegetation and habitat. “Habitat tradeoffs” in the region are often an important concept in the regulatory framework used to compare one habitat with another in evaluating a project. In addition, complementary and conflicting habitat interactions must be understood in the context of implementing a project that could complement or conflict with an adjacent CGI project, particularly in instances where different agencies or landowners are working in isolation to evaluate and implement projects. The permitting and regulatory process should help to cope with the conflict and aid in the coordination among landowners to a certain degree.

A fear of litigation and setting a precedent with unintended consequences is an issue closely tied to regulation. For example, implementing an ecologically-enhanced bulkhead or constructed reef would be considered “fill” under 6 NYCRR §661 and could potentially lay the groundwork for commercial real estate or other developers to build along the waterfront, further degrading the current shoreline ecosystem or exposing more assets to coastal hazards. Public health concerns and the reputations of the regional shellfish economy also create regulatory hurdles to CGI measures that might serve as shellfish habitat. In waters not open to shellfish harvest, there is a fear that potentially contaminated oysters could pose a public health threat as an attractive nuisance, endangering shellfish consumers and the regional shellfish economy. In other areas, there is simply a lack of understanding of what CGI are and how CGI operate; hence, the tendency is to support that which is most familiar and most easily understood by the public. CGI techniques that enhance traditional means of maritime engineering will need to have new models and regulations for maintenance and inspection; for example, regulations surrounding inspection practices for bulkheads may need to be modified to accommodate the preservation and encouragement of biogenic buildup due to ecologically-enhanced bulkheads. Educating the public and any stakeholders about the difference between CGI strategies and traditional engineering solutions, and the tradeoffs, is a necessary challenge. Traditional training of engineers does not focus on CGI; educating scientists and engineers on the benefits of CGI is critical to raising awareness and improving the success of CGI implementation.

Further research is required to address these concerns and should begin with targeted interviews or a forum with regulators and agencies on exactly what they need to feel comfortable permitting CGI. The HRNERR has begun a similar process and found it to be very instructive. Research should be conducted to analyze the existing regulatory framework to identify where there is flexibility in (and within the constraints of) the enabling legislation to permit something new and unproven in the region; specifically, what would be required to enable CGI to be granted a SAP. Additionally, work should focus on assessing both qualitative and quantitative costs and benefits that support or enhance the standard analyses that regulators use to evaluate CGI projects. To address performance concerns, more pilot studies are needed to demonstrate the successes and failures of CGI. These pilot studies need to be sufficiently large to obtain measureable scientific results and be funded for maintenance and monitoring over time. A better understanding of the habitat tradeoffs of CGI is critical for regulators, and more research is necessary in these areas to give regulators the confidence they need for permitting. To address more social concerns, research could target existing oyster reefs to track whether the oysters are subject to poaching. It might also assess how the public views CGI and identify what is needed to enhance the public's general understanding of it. The HRNERR at NYSDEC (Hauser 2012) has begun work on how the public perceives different shoreline types in the Hudson and research could build off that perception.

3. Literature Review

The safety of coastal populations has been based, in large part, on risk reduction through traditional engineering solutions, which often give little consideration to ecosystem potential and services (Spalding et al. 2014). However, recent studies present substantial evidence that coastal ecosystems can provide protective functions by dissipating erosive waves and buffering storm surge flooding while maintaining their other ecological services (Day et al. 2007; Fritz and Blount 2007; Feagin et al. 2010; Gedan et al. 2011; Ruckelshaus et al. 2013; van Slobbe et al. 2013; Spalding et al. 2013). A coastal risk reduction and resiliency study directed by the USACE was completed in September 2013, which discusses in part the capabilities of natural and nature-based features for mitigating coastal hazards and improving resiliency through an integrated approach that draws from the full array of coastal risk reduction measures (Bridges et al. 2013). Out of five natural and nature-based features in that report, three features, salt marshes, oyster reefs, and maritime forests, align well with some CGI strategies discussed in this report. Table 1 lists the primary coastal hazard mitigation and ecological benefits provided by six CGI strategies. Traditional engineering approaches that optimize safety often tend to be suboptimal with respect to other functions, such as ecological benefits, recreation, and aesthetics, and are neither resilient nor considered sustainable due to long-term and often costly maintenance (van Slobbe et al. 2013). To evaluate the performance of CGI strategies and to compare with traditional engineering solutions, performance evaluation metrics are proposed in Table 2.

The current state of the science related to the protective capabilities of natural defense systems is dynamic. Many academic and government entities have been exploring the real world complexity of how waves and surge interact with natural landforms and how living features boost the background ecosystem goods and services. The risk reduction benefits and ecological services of each CGI strategy are discussed in this section to lay the foundation for developing a research plan that helps advance the use of CGI strategies for enhancing the coastal resiliency of NYC. This section reviews the present understanding of the hazard mitigation and ecological benefits for the six CGI strategies selected for evaluation. For each CGI strategy, the review starts with a definition and description of the strategy, followed by an update on the sciences and identified unknowns. The definition of each strategy is depicted in all or some of the following aspects where applicable:

- target natural landforms
- typical sustainable locations in the ecosystem and site elevation
- horizontal scale and shape
- construction elements
- critical ecosystem-related structures and components
- key hazards addressed

The definitions are broken into these aspects to distinguish from each other, such that the literature review for each of these strategies concentrates on the principal characteristics. For instance, vegetation is the essential element of constructed wetlands and maritime forests and, therefore, a focal point in the section for that strategy.

Table 1. Benefits of CGI strategies in hazard mitigation and ecological enhancement

Benefits		CGI Strategies: Constructed wetlands / maritime forests	Constructed reefs	Constructed breakwater islands	Channel shallowing	Ecologically-enhanced bulkheads and revetments	Living shorelines (marsh sill)
Hazard mitigation	Storm surge/tide reduction	X		X	X		X
	Short wave attenuation	X	X	X		X	X
	Shoreline erosion control and protection	X	X	X		X	X
Ecological benefits	Water purification	X	X	X			X
	Fishery habitats provision	X	X	X		X	X
	Submerged aquatic vegetation habitats		X	X	X	X	
	Marsh habitats	X		X	X		X
	Forest habitats	X		X			
	Wildlife (e.g., birds, marine mammals) habitats	X	X	X	X	X	X
	Habitat diversity	X	X	X	X	X	X
	Carbon sequestration	X		X			X
	Air quality improvement	X		X			X
	Habitat diversity	X	X	X	X	X	X

Table 2. CGI strategy performance metrics

Benefits		Performance Evaluation Metrics
Hazard mitigation	Storm surge/tide	Surge height and/or flood depth; flood limit of target event (e.g., 100 years); phased delay of surge peak
	Wind wave	Wave height reduction; wave power/energy of return wave heights (e.g., 100 years) at shoreline
	Shoreline erosion	Shoreline retreat/accretion distance or rate; bathymetric and topographic variation
Ecological benefits	Water purification	Concentration of total suspended solids, harmful substances (e.g., harmful bacteria, heavy metal), dissolved oxygen, and nutrients (N, P, K); pH value; extent of water quality impairment; primary production (chlorophyll a)
	Fishery habitats provision	Catch Per Unit Effort; diversity index; characteristic species abundance; Young of Year or Juvenile Indices; patch size; utilization/occupation
	Submerged aquatic vegetation habitats	Density; biomass; diversity index; characteristic species abundance
	Marsh habitats	Density; biomass above and below ground; vegetation morphology (height, diameter); characteristic species abundance; diversity index
	Forest habitats	Density; biomass above and below ground; vegetation biomass; morphology (height, diameter, foliage); characteristic species abundance; diversity index
	Wildlife habitats	Bird diversity; characteristic species abundance
	Habitat diversity	Spatial heterogeneity; species richness; species abundance
	Carbon sequestration	Greenhouse gas (GHG) removal; GHG emission
	Air quality improvement	Concentration of ozone, particulates, and SO_2/NO_2

3.1. Constructed Wetlands and Maritime Forests

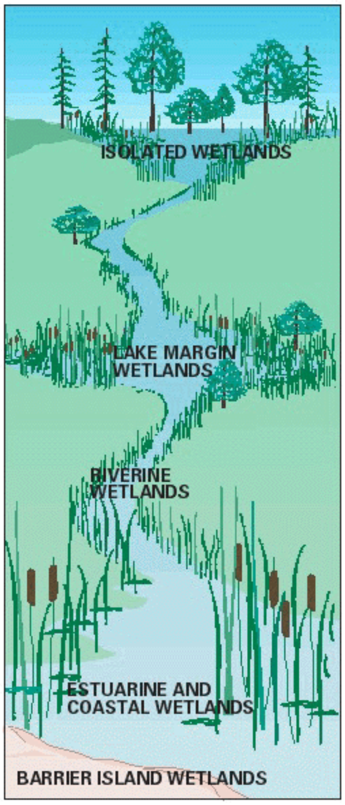


Figure 1. Wetland location within the watershed (Kusler 1983)

3.1.1. Strategy Description

Constructed wetlands are new or restored coastal wetlands that lie in sheltered and low-elevation areas from mean tide level to spring high tide level; are of irregular shape; may include perimeter protection features to retain soil and mitigate shoreline edge erosion; accommodate herbaceous vegetation, fishery, and wildlife habitats; and can dissipate wave energy, alleviate erosion, retard storm surge intrusion, and buffer tidal flooding. Figure 1 shows the location of coastal wetlands in the watershed system (Kusler 1983). In a general scope, coastal wetlands can be dominated by either herbaceous (marshes) or woody plants (swamps). In this report, constructed wetlands exclusively refer to salt or brackish marsh, i.e., coastal marshlands.

Maritime forests develop above the spring high tide level and are usually behind a secondary dune (Bain et al. 2007). The forests may connect to salt marshes through a transitionary zone of maritime shrublands and are found along coastal barrier islands and shoreline bordering sounds and rivers. The vegetation types which define maritime forests are unique because of their ability to withstand strong winds, periodic flooding, and damaging salt spray (e.g., Takle et al. 2007). Accordingly, maritime forests may act as an inland buffer to surge and waves during severe storms. The critical element for constructed wetlands and maritime forests is vegetation, which leads to similarities in mitigating coastal hazards and enhancing ecological functions. Therefore, the discussion on constructed wetlands and maritime forests has been grouped in this section. Figure 2 presents several images of a constructed wetland, coastal marsh, and maritime forest.

Figure 2. Diagram of constructed wetlands (NYC DCP 2013), wetland marshes (NYSDEC 2013), and maritime forest (Photographed by John W. McCord in Whitaker et al. 2009)

Numerous studies have recently been completed analyzing wetlands' and forests' protective functions (e.g., Krauss et al. 2009; Gedan et al. 2011; Shepard et al. 2011; Barbier and Enchelmeyer 2014). Wetlands and maritime forests of a sufficient size are a natural coastal defense and may be effective in providing wave dissipation (Anderson et al. 2011), flow impedance (Wu et al. 2001), and sediment retention. Consequently, these measures can improve erosion control and mitigate shoreline retreat (Wolanski 2006; Yang 1998; Shepard et al. 2011).

Particularly, maritime forests as natural vegetative barriers can reduce winds and obstruct salt spray (Takle et al. 2007). Wind speeds through forests can be reduced by more than 50% at a leeward distance of 20 times the forest height. This has been shown via studies of constructed windbreaks (Skidmore 1986; Wang and Takle 1996; Belcher et al. 2003). Directional wind reduction coefficients due to tree canopy are also often used in numerical models (Vickery et al. 2006; Luettich and Westerink 2010). Wind strength and salt spray reduction potential due to maritime forests can be estimated given existing studies; however, further verification against field measurements is recommended because forest trees vary in size and are arranged randomly and more coarsely than constructed windbreaks. Wind reduction and salt spray mitigation are less relevant to salt marshes and other CGI strategies reviewed in this document, therefore there will no further discussion. Wave attenuation, storm surge reduction and erosion control are the focus for event-based and gradual hazards.

In addition, constructed wetlands and maritime forests may provide ecosystem services like water purification, carbon sequestration, fish and/or wildlife habitat, and biodiversity. The benefits of this strategy are listed in Table 1, which vary based on the size or extent of the restored or constructed ecosystem, target habitat, landscape context, vegetation species community, hydrologic regime, and substrate properties.

There are some site-specific limitations to the use of constructed wetlands, such as the creation of habitat that attracts fauna within proximity to an airport, creating flight navigation and safety hazards. From a regulatory standpoint, fill placement in mudflats to restore eroded marsh is difficult to permit, although the issue is under further discussion with NYSDEC. The most notable limitations are due to the space requirement and needs related to strategy siting, sediment fill and erosion protection for vegetation until it becomes established in higher energy areas. Maritime forests are especially limited by the space requirements because a potentially large footprint is necessary to create a sustainable strategy. In the study on Target Ecosystem Characteristics (TEC) for the HRE, it was suggested that the creation of maritime forests requires a sufficient size (estimated at 200 acres or more) in order to maintain the minimum viable populations of the basic vegetative species (Bain et al. 2007). Additionally, size and siting conditions are further complicated by the fact that wetland and forest connectivity (e.g., fragmentation due to natural creeks or urban highway development) is an important factor to determining ecological benefits and hazard mitigation potential. Hence, the integration of constructed or restored wetlands and forests into the existing ecosystem is often critical to maximize the benefits of this strategy. Upfront studies to categorize shorelines with regard to the energy level of marine forces and existing variation in ecosystems are necessary to identify sites applicable to constructed wetlands, maritime forests, or other CGI strategies.

This strategy also requires considerable ecological expertise, long-term dedicated monitoring, and intensive labor. "Lack of basic scientific knowledge" and "lack of staff expertise" are two common problems contributing to the failure of implementation according to Kusler and Kentula (1989a, b). Although this publication is 25 years old, it is still relevant today. Sufficient up-front research and qualified staff expertise remain the keys to successful implementation of an ecosystem restoration project because the ecosystem is a complex, multi-faceted system. It is important to emphasize the uniqueness of each wetland and to make site-specific decisions for a successful wetland restoration and creation.

3.1.2. An Update on the Status of the Science

Studies on wetland creation and restoration, ecological benefits evaluation, economic assessment, and hazard mitigation potential have burgeoned in recent years. Books, manuals, reports, and journal articles have been published focusing on various objectives, ranging from case studies to general procedures and from project designs to monitoring approaches. Detailed discussion is focused on the ability and mechanism of vegetation to reduce wave heights and storm surge inundation depths and limits; improve ecological benefits; and adapt to rising sea levels.

Coastal Hazard Mitigation

Constructed wetlands and maritime forests mitigate coastal hazards in the form of vegetation-induced resistance, which can retard flow and dissipate wave energy for event-based and gradual hazards. Retreating shorelines can be protected from short waves and vessel wakes by this strategy due to the dissipation of wave energy. The hazard mitigation potential on a regional scale has been an active research area since the devastating tsunami in the Indian Ocean (2004), Hurricane Katrina (2005) and Hurricane Wilma (2005) in the Gulf of Mexico, and Hurricane Sandy (2012) in the Northern Atlantic. Following these events, many regional studies, most notably numerical modeling based studies, have been conducted. However, few of these studies are specific to NYC or the vegetative communities in the area.

With respect to the mechanism of vegetative resistance, evaluations of micro-scale flow structure, turbulence, and vegetal drag in a laboratory setting (Neumeier and Amos 2006; Lowe et al. 2007; Wilson 2007; Tanino and Nepf 2008) are most common in the existing literature. The effectiveness of vegetation resistance is dependent on internal factors such as stem density, height, wetland fragmentation, and wetland size, as well as external factors such as the intensity and forward speed of a hurricane. Table 3 summarizes various factors that affect vegetative resistance and thus determine the degree of wave energy dissipation and storm surge reduction. However, there are no direct studies stating the prioritization of those factors in hazard mitigation and wetland resiliency. Appropriately designed numerical experiments and field observations may assist to prioritize the most critical parameters.

Table 3. Impacts of the wetland and maritime forest properties on vegetative resistance

	Factors	Parameters	Impacts on Vegetative Resistance
Vegetation properties	Vegetation morphology	Height, stem/trunk diameter, branch, and foliage	Positively correlated
	Vegetation bio-mechanical properties	Stiffness of plant shoot (might vary seasonably)	Positively correlated
	Vegetation community	Stem density and communities arrangement	Positive correlated
Footprint	Wetland continuity	Distance to main coast, edge fractal dimension, and ratio of vegetated land area to non-vegetated area (water area, road area, swales, mudflats, etc.)	Intact wetland has the highest bulk resistance
	Horizontal extent	Distance in wave propagation or flooding direction	Positively correlated
	Vertical extent	Platform elevation	Positively correlated
	Topographic complexity	Arrangement of topographic features (hummocks, dunes, swales)	Unknown
Hydro-dynamics	Water surface elevation (surge height during a storm event)	Flow depth	Maximum resistance when flow depth is about the height of the vegetation (stem), i.e., near-emergent condition
	Wave climates	Wave height and wave period	Not in consensus

Among internal factors, emergent, stiffer, denser, and higher vegetation can dissipate wave energy, reduce inland storm surge height and extent, and limit tidal flooding more effectively than submerged, flexible, and short-stemmed vegetation (Nepf and Vivoni 2000; Nikora et al. 2001; Irish et al. 2008; Chen and Zhao 2012; Barbier 2013). An NYC-specific example is that the intrusive species, *Phragmites australis (Phragmites)*, is stiffer, taller, and denser than *Spartina alterniflora (Spartina);* thus, is anticipated to be more effective for reducing wave energy.

Salt marshes and maritime forests are often fragmented by natural or human disturbances; however studies on the effects of fragmentation patterns are rare. Understanding the effects of patch dynamics can help avoid the overestimation of protective value of these vegetated systems, while improving the design to promote a more effective arrangement.

Among external factors, wave attenuation rates are found to be less affected by wave heights and periods (Mazda et al. 2006; Augustin 2007; Augustin et al. 2009; Bradley and Houser 2009) than they are by water depth, vegetation morphology, stem stiffness, and the vegetated footprint size, shape, and elevation (Elwany et al. 1994; Lima et al. 2006; Lowe et al. 2007; Suzuki et al. 2008; Lövstedt and Larson 2010; Gedan et al. 2011). Water depth is a critically important external factor because vegetation resistance is most influential when the vegetation roughness layer takes up a sufficient portion of the total water depth (Nepf and Vivoni 2000; Wilson and Horritt 2002).

Using observation data, numerical models, physical models, or other tools (e.g., regression curves), metrics such as those listed in Table 2 can be applied to examine the hazard mitigation potential of proposed projects to guide project planning. An often-applied metric for evaluating the hazard mitigation potential of vegetation is hydrodynamic quantity (e.g., wave height, water level) reduction or a dissipation rate over a given distance. This is done by comparing wave heights or water levels inland of wetlands and forests to incident conditions at the seaward edge (e.g., USACE 1963; Fitzpatrick et al. 2009). Hazard mitigation can also be assessed using aggregated parameters, such as a percent reduction of total inundation volume over a given area. Additionally, at locations susceptible to erosion and scour, a horizontal retreat rate, as well as changes in vertical profile, can be used to evaluate mitigation of gradual hazards.

Field observations, e.g., wave heights, water levels, and currents along a designated transect, are useful to quantify the hazard mitigation potential of wetlands. However the costs of these field observations are typically high and in some instances observations must be gathered during specific time intervals (e.g., the attenuation of waves during storm events). Accordingly, timing and funding availability impact the success of field observation plans. Physical models are often more affordable and less affected by weather conditions, yet the applicability of these studies can be limited by the scalability of model results. Numerical models are robust tools and are commonly used to evaluate the hazard mitigation potential of CGI strategies (Loder et al. 2009; Wamsley et al. 2011; Barbier et al. 2013). In the instance of numerical models, the state of the science is continually improving, though many limitations still remain. How can numerical models be improved to more accurately predict the reduction in storm surge, wind waves and erosion due to vegetative resistance? How can field measurements and physical model setup support improvements of numerical models?

In many numerical models, the vegetative resistance under both oscillatory and steady flow is often lumped in with the resistance due to bottom friction. For instance, a Manning's coefficient is used to estimate the flow resistance due to various vegetation types (e.g., Bunya et al. 2010). Recent research has illustrated that Manning's coefficients for a given type of vegetation varies with time (e.g., seasonal), submergence degree, and flow velocity (related to vegetative stiffness). The variation may be profound during a storm event as vegetation flexes and breaks. However the sensitivity of modeled storm surge levels and waves due to a flow-condition dependent Manning's coefficient is not well understood. Empirical and theoretical formulas are available for estimating Manning's coefficients, drag coefficients, and vegetative resistance for a given set of field or laboratory conditions, which range from bio-physical properties of a single plant and plant community to physical flow conditions (Wu et al. 1999; Stone and

Shen 2002; Carollo et al. 2005). No study shows that existing formulas are applicable for the prevalent species in NYC. Hence, in order to implement a better parameterization of vegetative roughness in numerical models, it is important to understand vegetal drag and Manning's coefficients under both typical and stormy conditions for prevalent species in the NYC area.

Additionally, it should also be noted that numerical modeling based studies to date are often completed considering a two-way interaction between vegetation and either wind waves or longer period waves, such as surge or tides. In a real-world storm scenario, the interaction between currents, wind waves, and vegetation can be very complicated, especially during a storm event. Inherently, drag coefficients, wave frequency, and flow structure are affected by the three-way interaction in comparison to wave-vegetation, current-vegetation, or wave-current two-way interactions (Li and Yan 2007; Patil and Singh 2009). Storm surge level reduction, as a result of the vegetative resistance, limits the growth of wind waves. Wave breaking is arrested by the vegetation, thereby diminishing wave set up (Dean and Bender 2006; Augustin et al. 2008). Deflected, broken, or uprooted vegetation due to current-wave interaction enhanced shear causes a decrease in vegetative resistance; consequently, there is less wave attenuation and surge reduction (Zhao and Chen 2014). Understanding the effects of vegetation breakage and uprooting on both circulation and wave models is important for avoiding overestimation of vegetation effects. Ideally, the three-way interaction of waves, currents, and vegetation should be thoroughly considered in a coupled model system, yet this coupling is not present in most modeling efforts; the scientific communities' understanding is currently inadequate to provide guidance beyond basic principles. Hence, the interaction is often missing in models used to evaluate risk and scour reduction of a vegetated system such as wetlands and maritime forests.

Numerical models and the overall state of the science related to vegetal drag can be improved with additional insights based on field observations and physical modeling experiments. Field measurements during storm events are relatively rare due to costs associated with field observation and collection difficultly during severe storms. With improvements in data collection techniques, field studies are more feasible now than ever. Laboratory scale experiments on the other hand are more common and in general focus on short waves. These physical modeling based experiments can be used to fill voids in findings from field observation data, as well as to verify or improve existing numerical model assumptions. However, because physical experiments occur in a controlled environment, challenges remain to bridge the gap between small-scale laboratory findings and real-world storm scenarios. With validated vegetative resistance formula, numerical models can be used to simulate vegetation-induced attenuation of wave energy and flow momentum under various scenarios, including consideration of healthy, degraded, continuous and fragmented wetlands consisting of single or multiple vegetation types.

Ecological Benefits

In comparison to the hazard mitigation potential of coastal wetlands, the ecological benefits have long been identified. Since the 1980s, 34 studies were conducted with about 75 percent related to ecological services and 25 percent related to social benefits. It was determined through literature review that the ecological benefits of coastal wetlands could be grouped into the following categories: 1) wildlife habitat provisioning, including that of threatened and endangered species; 2) fisheries habitat provisioning; 3) biodiversity protection; 4) carbon sequestration and regulation of greenhouse gases; and 5) water quality improvement. Social services were grouped according to 1) tourism; 2) recreation; 3) education; 4) raw materials production; and 5) property value protection benefits. These categories are closely linked to the services identified in the NACCS (March 2014 Agency Review Draft), where a comprehensive list of ecosystem goods and services provided by a coastal wetland shows 17 out of 21 ecosystem services are ecological and social benefits related in comparison to wave-, tide-, and storm-related hazard mitigation benefits.

Among various ecological services, water quality improvement, fisheries habitats, and wildlife habitats are most studied while carbon sequestration and greenhouse gas (GHG: CH_4, CO_2, N_2O) mitigation are least studied. A recent study by Serena Moseman-Valtierra (2011) suggests that marsh ecosystems, which are thought to be major sinks of carbon, may, through anthropogenic disturbance, become sources of GHGs because plant rhizospheres in coastal sediments are sites of microbially mediated nutrient transformations, e.g., nitrification and denitrification. Salt marsh restoration in Jamaica Bay warrants greater attention regarding carbon sequestration, which is closely related to organic soil accretion and carbon content of the accreted soil (USACE 2014). There is uncertainty about the impact of anthropogenic nutrients on GHG production in wetland systems and how this should be considered in wetland benefits evaluation and constructed wetland strategy implementation. Quantification of GHG emission in coastal wetlands has become an important factor in evaluating wetlands protection and restoration strategy. While there is a growing body of literature documenting the ecological services of coastal wetlands globally, limited research exists for such systems in the NYC region. Furthermore, very little study has occurred to quantify the benefits of north Atlantic maritime forests.

A number of studies have shown various ways to estimate wetland benefits (e.g., Costanza et al. 2006; Liu et al. 2010; Costanza et al. 2008) and indicated the insufficiency of knowledge of key habitat values to support effective policy-making and management (Pendleton et al. 2007). Koch et al. (2009) suggests that dynamic modeling of ecological functions, greater field-based testing of the functional relationships between ecological condition and ecosystem services, and the economic valuation of those services will increase our accuracy in valuing coastal ecosystems and, in turn, refine ecosystem-based management practices. Only Wainger et al. (2013) evaluated ecosystem services for coastal wetlands within the NYC region. Additional studies should be implemented in the New York-New Jersey (NY/NJ) Harbor estuary to determine the regional value of these systems, how this value might differ in other regions, and why and how the highly urban nature of this region might influence ecosystem service values. For example, the high construction costs of restored wetlands cannot be justified by ecological and coastal protection benefits alone. Nonetheless, these systems represent a highly scarce resource in NYC that can be readily accessed by millions of people from a diversity of backgrounds. Future research should also address the influence of resource scarcity and population density on the social benefits of salt marshes in order to more comprehensively assess the value of restoring these systems.

In NYC, where open space is relatively scarce and land is valued at a premium, salt marshes often occur in a narrow fringe between developed infrastructure and mudflats or open water. There are economic and habitat tradeoffs associated with constructing new wetlands in these areas. In addition, while many of the ecological benefits (habitat or non-habitat) are related to community biomass and productivity of a given vegetation species, a special case of tradeoff caused by the invasive species common reed, *Phragmites,* exists as a conflict between shoreline protection value and bird habitat. *Phragmites* is an inevitable player in the context of sea-level rise, increased coastal inundation, and limited agency funding for management/maintenance of shoreline landscapes. *Phragmites* should be a focus in future studies regarding its potential for hazard mitigation and ecological impacts. As previously mentioned, this species could have a higher potential to dissipate waves than the native species marsh grass (*Spartina*), due to its rigidity and population density. However, it is also noticed that *Phragmites* is less attractive to birds and can harm bird habitat values. A recent study (Kiviat 2013) documented the important ecosystem services of *Phragmites* including non-habitat ecosystem services (e.g., water purification) and habitat ecosystem services (e.g., support for many common and rare species of plants and animals). The disagreement in *Phragmites* resultant habitat values or damages requires more research and field habitat data collection for a discerned conclusion.

These questions and concerns highlight the need for developing an ecosystem tradeoff assessment tool. Ecosystem tradeoffs are important indicators of project performance and a regulatory decision driver. For instance, assessing habitat tradeoffs by evaluating existing mudflat benthic and aquatic habitats values versus the planned constructed wetlands habitat values is necessary to understand the changes and impacts on ecosystem, thus deciding the placement of fill. Quantifying tradeoffs between *Phragmites* and *Spartina* can assist the decision on natural wetland management, e.g., whether *Phragmites* populated marshes should be restored to *Spartina*-dominated marshes.

Tools, models, and measures exist for individual services. The Water Quality Standards Handbook by the U.S. Environment Protection Agency (USEPA) lists a variety of water quality criteria in different forms (e.g., numeric criteria for wetlands). A Wildlife Habitat Benefits Estimation Toolkit was funded and developed by the Doris Duke Charitable Foundation through the National Council for Science and the Environment's Wildlife Habitat Policy Research Program (Kroeger et al. 2008). Habitat Equivalency Analysis, used in Natural Resource Damage Assessments, can be used to monetize ecological service units. Habitat Suitability Indices developed by the U.S. Fish and Wildlife Services (USFWS) are tools to quantify the value of various coastal habitats as they relate to habitat provision. Functional assessment models such as Evaluation for Planned Wetlands, Mid-Atlantic Tidal Wetland Rapid Assessment Method (MidTRAM), etc., quantify ecosystem functions for coastal wetlands. The Wetland Value Assessment (WVA) methodology is a quantitative habitat-based assessment methodology developed for use in determining wetland benefits of project proposals submitted for funding under the Coastal Wetlands

Planning, Protection, and Restoration Act (CWPPRA). The WVA quantifies changes in fish and wildlife habitat quality and quantity that are expected to result from a proposed wetland restoration project. These tools may not exist or be applicable for the NYC area yet. Further investigation is necessary to determine whether these existing tools can be adapted or adopted in the NYC region, as well as how these measures can be integrated to define the quality of wetland services. Note that many of these tools are not specific for a single type of landform features. These tools and relevant research requests are also applied to other strategies in this report when it comes to evaluation of ecological benefits.

To quantify and compare the ecological benefits, a reference site of a typical size (e.g., a control plot) needs to be determined prior to project design in order to score the overall performance in a context environment and for a target habitat type. The existing ecosystem services literature focuses largely on the use of case studies to measure and establish a value for ecosystem function. Approximately 300 case studies were screened by de Groot et al. (2012) to determine the value of ecosystem services across 10 biomes, including coastal wetlands. Meli et al. (2014) performed a meta-analysis of 70 experimental studies to assess the effectiveness of wetland restoration and identity factors that influence its effectiveness. However, replicated, controlled studies specific to the determination of ecosystem function have not been widely conducted and in particular have not been developed in the NY/NJ Harbor estuary. Additional analysis is required to evaluate whether such studies would be necessary and how they could be applied across multiple restoration sites being implemented by various agencies across NYC.

Key benefits should be identified at a given location and properly selected to meet goals and objectives of implementing this strategy. A set of standard metrics is desired for measuring the performance and prioritizing them in a hierarchy that can ensure the most important elements are to be accomplished first. The NACCS reports a series of metrics regarding various ecosystem goods and services of coastal wetlands and maritime forests for the Atlantic coast. Many of the ecosystem goods and services are dependent on wetland size, landscape context, and patch dynamics (Karen et al. 2000; Craig et al. 2012).

Landscape context and patch dynamics are related to wetland fragmentation, which can be caused by anthropogenic (such as roads, canal), climatic (e.g., storms), and internal disturbances (e.g., vegetated community competition). There are a variety of fragmentation metrics, for instance patch size (area), patch shape usually measured as a ratio of edge length to patch area (patch fractal geometry), distance to the nearest patch, and the amount of exterior habitat within a distance from the edge. Patch size is critical for a diverse breeding community, e.g. forest birds. Therefore, the amount of habitat within a patch is also important. For landscape context, nearest neighbor distance is commonly used, but does not work well in very patchy landscapes where the nearest neighbor patch may not be viable habitat. Instead, the proportion of area in similar or natural habitat type within a certain distance of the patch edge can be used (Anderson 2008). It is worth noting that ecology-driven patch complexity should also be fed back to hazard mitigation quantification. Otherwise it is easily to overestimate the hazard mitigation potential if the size of an intact constructed wetland is parameterized in a numerical simulation.

TNC and Nature Serve created an ecological integrity framework that was applied to wetlands (Faber-Langendoen et al. 2006). Many identified metrics were shared among the systems in that study, suggesting that a generic list of metrics could be developed, at least among broadly similar systems. Neckles et al. (2013) conducted a similar study that focused on salt marsh integrity and identified a set of metrics used to monitor integrity on National Wildlife Refuges (NWRs). These metrics were tested in the field, e.g., Long Island NWR Complex. These studies provide a promising framework and can be a "jump start" for advancing research of coastal wetlands and maritime forests in NYC. Similar and more specific studies should be proposed to review how ecological integrity indices developed in the literature can be adopted and improved for NYC. Such investigations would help natural resource managers balance the ecological, social, and coastal protection services of a proposed restoration site against the constraints of cost and availability of open space. Setting up pilot project(s) is a practical approach to perform controlled studies, collect data, test and improve various evaluation metrics, and examine effectiveness of project scales.

The effects of human activities on wetlands integrity and sustainability are significant in an urban area like NYC. Wigand et al. (2014) used census data, radiometric dating, stable nitrogen isotopes, and soil surveys to examine the temporal relationships between human population growth and soil nitrogen; they evaluated soil structure with computer-aided tomography, surface elevation and sediment accretion trends, carbon dioxide emissions, and soil shear strength to examine differences among disappearing (Black Bank and Big Egg) and stable (JoCo) marshes. At Black Bank, the biomass and abundance of roots and rhizomes and percentage of organic matter in soil were significantly lower, rhizomes larger in diameter, carbon dioxide emission rates and peat particle density significantly greater, and soil strength significantly lower compared to the stable JoCo Marsh, suggesting Black Bank has elevated decomposition rates, more decomposed peat, and highly waterlogged peat. In urban watersheds, salt marshes experience climatic stressors, such as accelerated sea-level rise; rising air and soil temperatures; increases in storm and drought events; and anthropogenic stressors, such as alteration of sediment supply and hydrodynamics, resulting in accelerated losses of marsh area as is now occurring within Jamaica Bay and elsewhere. Further research could identify relationships between multiple stressors and marsh elevation, size (overall area and width), and measurable ecosystem services, specific to highly urban areas such as NYC, which can afford managers and stewards an informed opportunity to maintain and restore coastal marshes in urban estuaries.

Drivers of Change: Failure Causes and Resiliency

The City's salt marshes and maritime forests have proven especially vulnerable and are increasingly in decline. For example, wetland loss around Jamaica Bay has been reported at an annual rate of 1 to 2 percent (Hartig et al. 2002; Swanson and Wilson 2008; Deegan et al. 2012). Maritime forests are contaminated by intrusive species and anthropological activities, such as recreation, highway clearing, and tree felling. The loss of salt marsh is attributed to extensive filling operations, dredging for navigation, and other impacts, including water quality degradation, erosion, and sea-level rise. Among those, big drivers for the stability of coastal wetlands and maritime forests are sea-level rise and sediment supply. Maritime forests survive at the supratidal zone, which may become the intertidal zone as sea level changes. However, maritime forests are less sensitive to sea-level rise than marshes and may collapse in subsequent marsh submergence. Relatively maritime forests are more subject to salt spray, wind, and waves under both normal and extreme weather conditions and climate change, which may deteriorate with a fragmented arrangement. For instance, the wind shear and salt spray can cause vegetation to die and then produce a new canopy angle on exposed forest surface. The study of a maritime forest on Topsail Island, North Carolina, demonstrated that 57 percent of the original aboveground vegetation was dead after 4 years of highway construction (clearing highway right-of-way). Other forest health issues (e.g., pests and pathogens, invasive species) are not trivial and may be part of a feedback loop with climate change (Dale et al. 2001). Invasive species (plants or insects) could dramatically degrade the health of maritime forests making them less resistant to marine forces and less resilient to changes due to storm events, droughts, etc. The bottom line may be that resiliency is not merely an output of construction but one of ongoing conservation/natural resource management on many fronts of ecological integrity for target (ecological) communities or ecosystem services/benefits.

Stability of coastal wetlands can be viewed in vertical and horizontal azimuths. Salt marshes can accrete vertically and expand laterally in response to sea-level rise and sediment supply (Nyman et al. 2006; Mariotti and Fagherazzi 2013; Kirwan et al. 2010). Adequate sediment load, at least 20 milligrams per liter (mg/L) for sea-level rise rates up to 10 millimeters per year (mm/year) (Kirwan et al. 2010), is necessary to maintain wetlands, based on a numerical study of eco-geomorphic feedback to global sea-level rise. The data from North Inlet, South Carolina (Morris 2010), as well as modeling efforts (Kirwan et al. 2010), show that the aboveground biomass is significant when the substrate is 1 to 2 feet below the mean higher high water level (*Spartina* at North Inlet) and the accretion rate increases as sea level rises. With human intervention (e.g., experimental fertilization), the boosted biomass production can improve the adaptability. Although fertilization may not be recommended, nutrient load is typically higher in urban areas than in other areas, which may potentially enhance the adaptability. Nyman et al. (2006) even found that the marshland vertical accretion varied with organic accumulation rather than mineral sedimentation across a wide range of conditions in coastal Louisiana. The vertical accretion of marsh is also affected by sediment supply and tidal range. Expansive marshes in regions with low tidal ranges will likely submerge in the near future, even for a high suspended sediment concentration and conservative projections of sea-level rise (Kirwan et al. 2010). In contrast, in a region with a broader tidal range, marshes are more adaptable to sea-level rise, especially with a high suspended sediment concentration. Because of the organic accumulation and high biomass-enhanced sedimentation, wetland accretion will likely keep up with the pace (Kirwan and Mudd 2012).

Lateral expansion of coastal wetlands is more dynamic and it is unlikely to maintain a dynamic equilibrium because processes responsible for marsh expansion, such as freshwater input dictated sediment supply and nutrient load, are weakly or not linked to processes responsible for marsh erosion, such as wave climate, which is largely disconnected from the presence of rivers and rainfall runoff (Fagherazzi et al. 2013). Therefore, coastal wetlands are laterally unstable due to wave action and edge erosion with or without sea-level rise (Fagherazzi et al. 2013; Mariotti and Fagherazzi 2013).

Successfully applying the strategy of constructed wetlands requires extensive knowledge of flooding frequency, wave climates, ice climate, sediment supply, and marsh biological properties and ecological dynamics. The interpretation of how the drivers and stressors that contribute to wetland loss threaten restored wetlands, and their associated ecosystem benefits, can inform the selection of restoration sites and the maintenance of restored wetlands to maximize the long-term sustainability and ecosystem services of coastal wetland systems. Reducing the threat to coastal vegetation from development, sea-level rise, and other natural and anthropogenic factors would help to protect many coastal regions against storm surges. For instance, wetlands in Jamaica Bay developed by the USACE in 2013 were severely damaged by ice over the winter. Additionally, due to urbanization and minimized sediment inputs into water bodies like the Hudson River and Jamaica Bay, sediment starvation of coastlines will have an impact on wetland sustainability in NYC. Sediment starvation of coastlines produced by river dredging and damming is a major anthropogenic driver of marsh loss along the U.S. Atlantic coast and generates effects at least comparable to the accelerating sea-level rise due to global warming (Mariotti and Fagherazzi 2013).

With sufficient sediment load and nutrient load, constructed wetlands and maritime forests are a sustainable strategy that can self-adapt to gradual hazards, such as sea-level rise, and can self-recover from moderate damage due to storm events or ice cover. However, how to quantitatively assess the coastal resiliency needs further study. Sea Level Affecting Marshes Model (SLAMM), Marsh Equilibrium Model (MEM), and other ecology models exist for simulation of wetland evolution. What aspects of these models should be improved? Can they be adopted in NYC? A Coastal Resilience Tool (CRT) was developed by TNC and is available at http://www.coastalresilience.org/. The CRT is a geographic information system (GIS)-based mapping portal, which exhibits present and future flood and sea-level rise hazards, habitat development, and a variety of wetland context at a coarse level. This tool can be a framework of resiliency assessment for the NYC region.

3.1.3. Unknowns and Data Gaps

The following unknowns and gaps were identified by the research group for the strategies of constructed wetlands and maritime forests.

Vegetative Resistance and Hazard Mitigation Potential

- How resistant are coastal wetlands and maritime forests to marine forces under a wide range of turbulent conditions?
- What are the appropriate formulas to estimate vegetative resistance for a wide range of submergence degrees (from emergent to deeply submerged)?
- How can field measurements and physical model setup improve the understanding of vegetative resistance (Manning's coefficient) of prevalent species of coastal wetlands and maritime forests in the NYC region?
- How can a physical model be set up to help improve the understanding of friction coefficients for prevalent marsh species in NYC coastal habitats, e.g., *Phragmites* and *Spartina*?
- How can critical factors impacting hazard mitigation potential be prioritized, e.g., bio-mechanical properties, platform elevation, size, wetland continuity, proximity to other natural areas, incident wave conditions? Which data are already available?
- What are the bio-mechanical properties of prevalent marsh species in NYC coastal habitats, e.g., *Phragmites* and *Spartina*?
- How can numerical models be improved to more accurately predict the reduction in storm surge, wind waves and erosion due to vegetative resistance?
- How sensitive are storm tide, wave, and erosion predictions to flow-condition dependent Manning's coefficients versus a constant one for NYC-specific numerical models?
- At what scale (horizontal and vertical) are constructed wetland and maritime forests effective at dissipating wakes and waves and reducing surge?
- How can patch complexity and dynamics (e.g., fragmentation, patch expansion and degradation) be parameterized in numerical models?
- How do patch dynamics affect the hazard mitigation potential?

Ecological Benefits

- What are the ecological tradeoffs: *Phragmites* versus native marsh like *Spartina*, or no marsh?
- Should the mudflats or open water be filled to be converted to a large wetland?
- How would the environment be affected?
- How much larger is adequate to effectively provide ecological benefits?
- What are the habitat tradeoffs?
- What field data need to be collected in order to improve tools to conduct an in-depth analysis of tradeoffs such as shoreline protection versus bird habitat restoration, native habitat heritage conservation versus other environmental and ecological values, and existing habitat values versus transformed habitat values?
- What aspects of models like SLAMM and MEM should be improved to improve the understanding of wetland evolution? Can they be adopted in NYC?

- Which natural wetland systems can be used as control sites to benchmark ecosystem values for project(s)? Can pilot projects be identified as benchmarks and how?
- What are the minimum pilot project scales for providing targeted levels of protection and ecosystem services?
- What are the metrics to best monitor wetlands and their associated habitats?
- How are scorecards best designed to quantify overall ecological benefits provided by maritime forests and coastal wetlands in the NYC region and rank proposed projects to facilitate decision making? Can a set of standard metrics be combined to index the performance of projects?
- How does the highly urban nature of NYC influence ecosystem service values of constructed wetlands and maritime forests, including fragmentation due to roads, nutrients load, and other pollution effects?
- How are studies best implemented in the NY/NJ Harbor estuary to determine the regional value of wetland and maritime forest systems, how this value might differ in other regions and why and how the highly urban nature of this region might influence ecosystem service values?
- How can the understanding of GHG emission in wetland systems be improved and how this should be considered in wetland benefits evaluation and constructed wetland strategy implementation?

Resiliency of Constructed Wetlands and Maritime Forests

- Which areas have sufficient sediment supply for sustainable wetland systems?
- How adaptable are *Phragmites* and *Spartina* to sea-level rise?
- What is the self-recovery time scale and affecting factors for maritime forests and coastal wetlands?
- Which is the critical depth of filled sediment suitable for rooting, above which plants are most vulnerable to uprooting, freezing, and preying?
- How to quantify the static and dynamic ice forces being exerted on natural shorelines?
- How can the understanding of ice volume and coverage in the area, as well as the expected vegetation uprooting forces accompanying it, be improved upon?
- How can the resiliency (or vulnerability) of coastal wetlands and maritime forests be quantified? Can existing resiliency evaluation tools, e.g., the CRT developed by TNC, be improved to examine resiliency considering present and future flood and sea-level rise hazards for NYC?
- How is the resiliency affected by the urban settings of NYC?

3.2. Constructed Reefs

3.2.1. Strategy Description

Constructed reefs are artificially made reefs that lie in shallow water, submerged or emergent; are generally parallel to the shoreline; are constructed from environmentally safe, durable material; often accommodate shellfish or finfish; and can dissipate erosive wave energy. Constructed reefs can be made from a variety of eco-friendly materials such as rocks and other substrate that encourage shellfish settlement and/or habitat changes favorable to other aquatic species such as finfish. Constructed reefs can be designed for a variety of goals including wave attenuation, the creation of shellfish and fish habitat, protection of endangered habitats, creation of recreational diving areas, and others, but may not be limited to a single function. Figure 3 presents images of constructed and living reefs.

Figure 3. Diagram of constructed reefs (NYC DCP 2013) and photo of living reefs (Katlin Walling)

Although constructed reefs provide habitat for multiple shellfish and finfish species in the NYC area, this study often discusses oyster habitats in detail as an example of ecological benefits specific to a given species. This is both due to the availability of information related to oysters and the fact that, along with mussels, oysters are the dominant species that are capable of growing rapidly in brackish water and colonizing the constructed substrate near estuarine river mouths and in nearshore areas (Rella and Miller 2012).

Naturally occurring living reefs often serve to protect fragile shorelines and marshes and their economic and ecological values. Unfortunately, many natural reefs have disappeared due to natural or anthropogenic causes (Kroeger 2012; Rella and Miller 2012). Constructed reefs can function as breakwaters when placed at emergent (high-crest) or near-emergent (low-crest) elevations. This strategy is a well-established method for protecting and stabilizing shorelines in sheltered areas. For instance, constructed oyster reefs in Mobile Bay have been designed to reduce wave heights and energy by 50 percent or more, reducing shoreline erosion and associated damages to private property and public infrastructure. The local economic value of this wave attenuation may be large, based on evidence from other studies that looked at property values and insurance premiums for coastal U.S. areas (Kroeger 2012).

Innovative design of artificial reef units, such as reef balls (Reef Ball Foundation Inc.), pyramid fish haven (Living Shoreline Solution Inc.), and other eco-friendly designs (Reefmaker Inc.) enhance their ability to attenuate waves without blocking free water flow. These designs can be optimized to specific criteria. Some reef unit designs are optimized for shellfish, while others are optimized for finfish. For instance, some artificial reef structures, under suitable external conditions, are designed to be inhabited by finfish species during post-larval stages, with the reefs providing shelter and access to food.

When lacking a native community for supporting reef growth, implementation of constructed reefs typically begins in a controlled environment. In the case of shellfish, the larvae of the species naturally seek out a hard surface to settle upon and therefore a substrate must be provided. After the nursing period is complete, the shellfish can be permanently planted offshore. With time, generations of the species continue to grow and large reef structures are eventually formed. As these reefs develop, they also provide critical aquatic habitat. Reefs, constructed or natural, serve as breakwaters, stimulating deposition in the quiescent areas behind the reefs where vegetation takes root. In addition, constructed reefs can provide important ecological functions such as water filtration to improve water quality. They allow the shoreline to retain many of its natural features, neither affecting the natural curvature of the shore nor the view of the stream bank or bay (Rella and Miller 2012).

Although constructed reefs are desirable from an ecological viewpoint, they are strictly limited by many environmental factors. For instance, along the north Atlantic coast, reefs are highly susceptible to damage from debris, ice, and sometimes longshore shifting sediment (Taylor and Bushek 2008). Additionally, oyster reefs are limited to low to medium energy environments with a small to moderate tidal range. Finfish and other species are additionally sensitive to these external factors and further piloting and testing studies are required for high wave energy environments for a variety of reef types. Temperature is another environmental concern for reefs, particularly those targeting shellfish habitats. A study on oyster colonization in the HRE linked the success and demise of oysters to warm-cool cycles during the Holocene (Carbotte et al. 2004). However, there is still the potential for development of intertidal oyster reefs in temperate estuaries along the north Atlantic coast. Lastly, in New York Harbor areas, water quality and current velocity may be two of the most important factors limiting reef colonization due to pollution discharges (Chin-Sweeney 2003; HRE 2009; Zarnoch et al. 2012).

From a maintenance and safety standpoint, constructed reefs must be clearly marked to avoid navigational hazards and human injury due to abrupt changes in slope and depth of the shoreline, particularly in heavily trafficked areas. An additional safety concern is the introduction of contaminated oysters into food markets and the associated increases in public health risks. Regulatory requirements are very strict for oyster reefs to prevent illegal oyster harvest.

3.2.2. An Update on the Status of the Science

Coastal Hazard Mitigation

Because of the limited horizontal dimensions, constructed reefs do not provide substantial storm surge reduction. However, constructed reefs break and dissipate short waves, and hence are being used to reduce shoreline erosion caused by storms and boat wakes (Scyphers et al. 2011). Many reef types have been successfully constructed to protect residential properties located along the banks of small estuaries, e.g., Virginia's Artificial Reef Program (http://mrc.virginia.gov/vsrfdf/reef.shtm). Whether or not the construction of large-scale reefs in more open water would be equally as cost effective as those in a semi-closed environment remains a question. A tremendous amount of substrate material might be required to construct large-scale systems, and they could create unacceptable hazards to navigation depending on where they would be constructed.

To evaluate the hazard mitigation performance of constructed reefs, a wave transmission coefficient indicating the portion of wave energy transmitted from the unprotected side to the protected side is a common parameter. Although the relationship of this parameter with traditional breakwater dimensions is developed from model tests and field observations (e.g., the Coastal Engineering Manual [USACE 2002]), understanding of wave transmission effectiveness over constructed reefs with various reef unit designs is limited. Three-dimensional numerical models that can resolve the characteristics of pierced reef units are useful to simulate wave propagation and to quantify wave transmission coefficient.

A high-crest reef will be more effective in dissipating wave energy due to its bathymetric and topographic resistance; however, it has been noted that a near-emergent reefs (closer to mean sea level) will be less exposed to intense forces and more likely to survive. Additionally, the length of uninterrupted reef will have a direct effect on the stability of the overall structure, as well as the level of protection. The gap along the length of the project between two reefs should not be larger than 2 times the individual reef length and generally is around 2 times the bay indentation (the maximum offset of the embayed beach from a line connecting adjacent breakwaters according to the headland breakwater studies (Hardaway and Gunn 2010). These rules need further verification for constructed reefs if designed as modified living breakwaters. In addition, drainage, elevation changes, recreational access, and sinuosity of the project should all be considered in the final design. For oyster reefs specifically, more design guidance can be found in the Oyster Reef Habitat Restoration (Luckenbach and Coen. 2003) and the Oyster Habitat Restoration Monitoring and Assessment Handbook (Baggett et al. 2014).

Ecological Benefits

Constructed reefs can be used independently or used to enhance constructed sill, revetment, bulkhead, or breakwater structures ecologically. Similar to their stone counterparts, constructed reefs allow for a significant amount of habitat development in nearshore areas, e.g., finfish, shellfish and lobster habitat. By decreasing the amount of energy in the water shoreward of a structure, marine fauna and flora can become established in areas where wave energy would normally be too intense for these habitats to develop. Properly designed constructed reefs with appropriate crest height and window spacing allows for circulation, preventing the water behind it from becoming stagnant. Circulation must also allow nutrients and harmful pollutants from upland sources, which normally enter the water during periods of heavy rain, to exit the area behind the sill in order to prevent negative impacts on marine life. Animals that are attracted to these areas include waterfowl and small mammals that feed on the seeds from the marsh plantings, invertebrates (fiddler crabs, snails, amphipods) that feed on the organic matter in the soil, and fish that feed on the organic matter of broken-down plant and animal material (Miller et al. 2014).

Although constructed reefs have claimed many benefits, they still require careful regulation and planning, especially when non-natural material is used as the substrate. Environmental and ecological concerns include toxicity, damage to ecosystems, and concentrating fish into one place (e.g., may cause overfishing). The effects of constructed reefs on the economically important species need be studied prior to implementation. Ecopath with Ecosim (EwE) is a mass-balance assessment model, commonly used for fish species evaluation, which can estimate snapshots of biomass for a given species at any time after implementation of a project. Application of EwE in the city area requires accurate baseline knowledge of reproduction, migration, mortality of a critical species, and its linkages with other species. The information on benthic habitats and critical species that can serve as indicators of the natural in the area remains a large gap, which prohibits understanding of environmental and ecological impacts of constructed reefs on existing ecosystem. In addition, effects of environmental variables on growth charts of critical species (shellfish, fish, lobster, etc.) need to be monitored in pilot projects. Baggett et al. (2014) built upon previous documents that provide more general monitoring recommendations or site selection guidance (e.g., Brumbaugh et al. 2006). It provides a good framework for designing, monitoring, and measuring reef habitats. A field test should be conducted to apply and exam the rules and metrics proposed by Baggett et al. (2014) in the New York Harbor area for creating sustainable constructed reef projects.

Numerous studies have examined oyster reef benefits specifically. The Oyster Restoration Research Project (ORRP) in NYC, completed in 2012, studied five pilot oyster restoration projects (Bay Ridge Flats, Governors Island, Hastings, Soundview, and Staten Island) and developed four criteria for determining the oyster restoration potentials. The criteria include spat-on-shell, survival and growth, natural recruitment, and environmental conditions. The Soundview site had the best overall development patterns indicating the best prospects for successful restoration efforts. Lessons can also be learned from successes and failures of previous implementation of oyster reefs in other places, such as optimal placement (Grabowski et al. 2005; Swann 2008; Scyphers et al. 2011; Grabowski et al. 2012; Kroeger 2012; zu Ermgassen et al. 2013).

Oysters and mussels are filter-feeding organisms and internally concentrate any harmful pollutants present in the water (NY/NJ Baykeeper 2005). Oysters have been described as a keystone species because they provide valuable ecosystem services for their habitats (Ravit 2012). This colonial species form reefs that provide food and nesting habitat, as well as sequester carbon, recycle biological material, and boost benthic productivity (Risinger 2012). Oysters can dramatically improve water quality (NY/NJ HEP 2012). An adult oyster is capable of filtering as much as 50 gallons of water per day (NY/NJ Baykeeper 2006). This filtering reduces the turbidity of the water and the nutrient load, while increasing levels of dissolved oxygen (Ravit 2012). Due to their ability to support other organisms and define a community, the oysters are considered to be the ecosystem engineers of the water in which they inhabit (NY/NJ HEP 2012).

Drivers of Change: Failure Causes and Resiliency

A constructed reef is subject to the same modes of failure as any other sloping-front structure, such as sill, breakwater, or revetment. As waves reflect from the front and ends of a stone structure, the water's motion will scour the toe and flanks of the structure. Scour around any structure is typical, and continued erosion may result in the structure slumping or the shells moving. This will decrease the effectiveness of the structure to work as a breakwater but can be prevented with routine inspections (Miller et al. 2014). Scour concerns should be less with constructed reefs which are colonized successfully; years of successive settlement of larval oysters on adult oyster shells provide levels of surface and interstitial heterogeneity that are rare in marine ecosystems (Bartol 1999). Such surface complexity will be effective in further dissipating the waves and reducing the levels of reflected energy. Additionally, if the ground beneath reefs is not properly compacted prior to placement, the soil will sink due to the weight of the structure. Oyster growth is very dependent upon their position within the water column and habitat structure (Lenihan 1999). Sedimentation from being too close to a river or bay bed can reduce growth rates and increase mortality rates of oysters (Miller et al. 2014).

Historically, living reefs have been more commonly constructed in locations such as the Chesapeake Bay and Gulf of Mexico where ice does not need to be considered. However, ice should be considered into the design when constructing a living reef in the Northeast. Floating ice, acting similarly to other types of floating debris, can apply large forces to the reefs, causing structural damage and in the case of living reefs, crush the shells forming them. Additionally, when ice becomes frozen to the structure, entire sections of the structure can be uplifted due to buoyant forces at high tide. In most cases, the damage due to ice freezing to the reef structure will cause a gradual failure (Miller et al. 2014). In addition to structural damages from ice, some species require specific temperature regimes to survive. For instance, oysters can survive dormant in cold water but will die if exposed to cold air; therefore, it is important to ensure that the oysters remain completely submerged during low tide (NY/NJ Baykeeper 2005).

One of the most important considerations and normally a limiting factor is the water quality. The HRE had significant populations of eastern oysters (*Crassostrea virginica*) prior to the 1920s (Zarnoch et al. 2012). A combination of overfishing, pollution, and habitat destruction led to the loss of both the oyster fishery and the ecological services oysters provide. Both oyster and mussel reef systems require specific conditions in order for the species to thrive and become self-sustaining. Salinity is the most important factor influencing the growth and survival of oysters and mussels. Oysters can tolerate a wide range of salinity in the intertidal zone (Risinger 2012), ranging from 5 to 40 practical salinity units (psu), with 14 to 28 psu being an optimal range (Galtsoff 1964). Concerns with developing oyster reefs in an estuary or bay include the oyster's susceptibility to freshets, pulsed freshwater events from melting snow and ice at the end of the winter, and triggered disease risks (Buzan et al. 2009). A freshet can have a large impact on the salinity of the lower portion of an estuary with a large river discharge like the Hudson, dramatically affecting key ecosystem processes (Steimle 2005; Rella 2014) and triggering oyster disease (Buzan et al. 2009). In addition, shell-based reefs will need to be stocked with oysters at a density that will maximize fertilization. Mortality is likely to occur due to predation (e.g., oyster drills) and MSX (multinucleated sphere unknown) disease; thus, reefs may need to be continuously monitored and stocked to maintain optimal density (Ewart et al. 1993; Zarnoch et al. 2012).

3.2.3. Unknowns and Data Gaps

The following unknowns and gaps were identified by the research group for the constructed reef strategy.

Impacts of Constructed Reefs on Flow Dynamics and Wave Transmission

- What are the flow patterns through reef units? How are the flows affected by the shape and the void space of the unit?
- What is the circulation pattern behind structures? How is that related to the residence time of the tranquil water?
- What are the wave transmission coefficients of various artificial reefs?
- How do project properties such as footprint shape, proximity to coast and crest elevation affect wave transmission over reefs?
- How does the surface roughness of reefs affect wave transmission?
- How would sedimentation behind the reef be impacted?

Ecological Benefits

- Which pilot studies are required to determine the minimum project that are necessary for effective wave dissipation and significant ecological benefits? How does the project scale affect oyster implantation and colonization?
- What field tests should be conducted to exam the rules and metrics proposed by Baggett et al. (2014) in the New York Harbor area for creating sustainable constructed reef projects?
- What are the relevant ecosystem models currently available? What are the limitations of those models? How to improve the basics of those models, e.g., increase spatial and temporal resolution, include more stressors? How to relate those models for NYC? What are critical aquatic fauna species? How do the aquatic fauna species respond to environmental variables, such as salinity, turbidity, and chemicals?
- How can benthic habitat information be efficiently collected and catalogued for analyzing habitat displacement and evaluating ecological impacts of reefs and other in-water CGI strategies?
- What are possible structural benefits achieved by developing oyster reefs on marine infrastructure (i.e., effect on structural strength, chloride penetration, physical forces absorption)?

Constructed Reefs Feasibility and Stability

- How can acceptance of constructed reefs be improved? Can experimental projects and monitoring protocol be developed to document and bridge the potential difference between findings and data collected in other regions?
- Which are the critical factors (water quality, substrate chemical, social) in NYC destroying oyster reefs?
- How oyster colonization and shellfish and finfish populations are affected by flow speed and circulation patterns?
- Would the construction of large-scale reefs in more open water be equally as cost effective as those in semi-closed environments?
- What data are available for reefs in a high-energy environment for NYC and other regions? How can pilot projects be setup for testing reefs in a high-wave energy environment and what parameters need to be monitored?
- How can knowledge regarding wave climate, including boat wakes which are often more important than wind wave, be improved to aid in the design and planning of constructed reefs? Where are critical sites to monitor waves and wakes? How much do the wakes change between their point of generation and the shoreline in different portions of the Hudson? Are the existing vessel wake formulas accurate enough for use in NYC?
- How can larval transport be assessed at a harbor scale?
- In addition to the ongoing ORRP oyster reef study, which additional tests are needed to improve oyster reef implementation? What studies are necessary for other reef types targeting species like finfish?
- What is the optimal crest elevation, considering structure stability and resiliency?
- What are the properties of oyster substrate that determine oyster growth and multiplication and how? What are the impacts of MSX and oyster drill in NYC reefs? Is there a time period, relative to reef construction, in which oysters are most vulnerable to MSX and oyster drill?
- How can the forces from floating ice, buoyant forces from ice during high tide, as well as the pressure from sheet ice piling up along a shore be further understood? Can we consider further limiting any interaction between the shellfish and the ice if a maximum predicated ice thickness could be determined for the project site?

3.3. Constructed Breakwater Islands

3.3.1. Strategy Description

Constructed breakwater islands are artificial islands that mimic sand bars, wetland islands, or barrier islands that are built at emergent elevations in offshore shallow water areas; are narrow structures with mild lateral slopes; are constructed through offshore nourishment or by using geotextile tubes filled with dredged material to create a base, then filled with rock or sand; can be integrated with some or all of the following: beach, dune, swale, beach grass, marshes, back barrier marsh, maritime shrub/forests, living reefs, and/or SAV to create shorebird and marine organism habitats; and protect seafront areas from wave forces.

A breakwater island can be considered as a functional combination of an artificial island and a breakwater. The main coast at the lee side of the constructed breakwater island is sheltered from erosive waves under either normal or more extreme weather conditions. Furthermore, surge height may be reduced on the protected side of the breakwater because surge overtopping can be limited or redirected (Stone et al. 2005; Otten et al. 2006) during low-intensity, frequently occurring storms. Consequently, less flooding and erosion stimulate sediment accumulation, especially when sediment supply is sufficient.

Unlike the multi-layer traditional breakwater, this strategy includes a core installation (e.g., marine mattress and geotextile tubes) and a surface layer of sediment nourishment. The constructed breakwater island appears more natural than traditional breakwaters and provides ecosystem goods and services by establishing coastal wetlands, maritime forests, SAV beds, and living reef substrate. Figure 4 shows a conceptual design of a constructed breakwater island in the Fort Pierce Marina, Florida. This project creates an island area of 15 acres and a total habitat area of 21 acres, including oyster habitats, mangrove communities, coastal dune habitats, seagrass recruitment, and shorebird habitat.

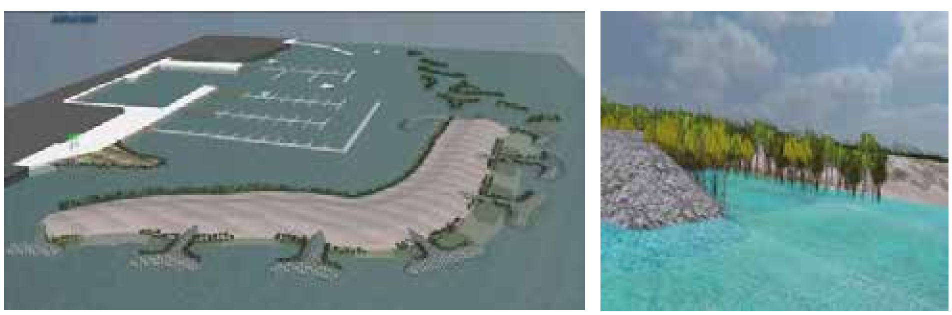


Figure 4. Conceptual view of a constructed breakwater island in the Fort Pierce Marina, Florida (Czlapinski 2013)

Because habitat types differ considerably between Florida and NYC, appropriate species should be carefully introduced in the planning and design phase of this strategy along the NYC coast. Key species can be found in the New York Natural Heritage Program (Edinger et al. 2014). For instance, northeastern shrubs such as bayberry (*Myrica cerifera*), marsh elder (*Iva frutescens*), and salt bush (*Baccharis halimifolia*) are potential species.

In addition to the hazard mitigation potential and ecological benefits, this strategy also has economic and social benefits. In an area where erosive waves are prevalent, constructed breakwater islands can provide protection while utilizing less space for development, reusing dredged material, and maintaining access to the waterfront.

The challenges associated with this strategy are planning, permitting, and constructing and maintaining a large in-water structure that requires an underwater installation along with a large volume of sediment fill. Both site planning and nourished sediment retention are critical to a successful, functional, and structural design. Poorly placed islands may become sediment sources for navigation channel shoaling or adversely impact marinas and other areas intended to benefit from the strategy. Furthermore, unstable surface sediment may lead to an eroded island and eventual project failure. Therefore, comprehensive hydrological, hydrodynamic, and sediment dynamic studies are necessary to aid the entire process from design to implementation.

The up-front capital costs can be significant when compared to traditional breakwaters while the construction cost varies with project sites. Due to the requirement for substantial sediment fill, a constructed breakwater island would be more cost effective in a shallow water environment where it would not require as much fill.

3.3.2. An Update on the Status of the Science

Artificial islands and breakwaters in isolation are fairly well-established strategies; meanwhile, a constructed breakwater island integrates the natural elements of an artificial island with the engineering features of a detached breakwater. The island reclaims land from the sea, enhances habitat diversity, and protects mainland coastal communities from marine forces, such as storm tides and waves. The mechanism of attenuating waves and the potential to create habitat relatively are well known, but may not be achieved without considerable study of a given project site. Active research for this strategy is more site specific and project oriented than fundamental. Optimal project footprints, crest elevations, types of mosaic habitats, and filling material should be addressed by studies in advance in order to facilitate planning, designing, and constructing. Most importantly, the reuse of dredged material, the definition of design storm events, and the natural littoral sediment budget are essential subjects to be explored in future research.

Coastal Hazard Mitigation

As a shoreline protection strategy, a constructed breakwater island inherits the hazard mitigation functions of conventional breakwaters and natural barrier islands. Impacts on storm surge and wind waves for this strategy result from the frictional and bathymetric resistance related to the bottom roughness and the landform’s shape. In cases where islands include marsh or forest ecosystems, vegetative resistance can play a role as well. Barrier islands and peninsulas can provide protection to waterfront communities from coastal storms (Benavente et al. 2006; Rosati 2009; Grzegorzewski et al. 2008; Grzegorzewski et al. 2011) while also providing ecological value. Rego and Li (2010) reported that a natural barrier system with a sufficient crest height can block and redirect the intrusion of storm surge based on numerical simulations of Hurricane Ike (2008) in Galveston Bay, Texas, for a wide range of barrier system conditions (e.g., existing, eroded, breached, flattened, and submerged). Aretxabaleta et al. (2014) demonstrated that barrier islands can reduce the semidiurnal tide transmission from offshore to a bay area. In the 2014 study, only 20 percent of the offshore semidiurnal tidal amplitude transferred into Great South Bay behind Fire Island along the coast of Long Island, New York. Thus, if a constructed breakwater island successfully mimics a naturally occurring barrier island, there is significant potential to reduce both spring and storm tide water surface elevation. However, the effectiveness is limited by its crest elevation and horizontal scale.

Constructed breakwater islands more effectively dissipate shorter-period fluctuations, such as wind waves, than long waves, such as tides and storm tide. Short waves that have wave periods up to tens of seconds are more sensitive to bathymetric changes and bottom friction when water depth becomes shallow. A constructed breakwater island breaks and dissipates short waves, protecting shorelines from erosion or wave action. Wave attenuation rates vary with different combinations of constructed and natural elements. For instance, vegetation planting on the island surface can increase the surface roughness, thereby increasing the wave attenuation potential. When attempting to optimize hazard mitigation using this strategy, design considerations should include the benefits of reefs, beaches and dunes, and wetland and maritime forest habitats on short wave attenuation.

Reduction of long waves is more difficult to account for in the design of these strategies, as necessary length and width scales of the island may be substantial in order to have notable influence on tidal level and/or storm induced water level fluctuation. Additionally, gradual hazard erosion mitigation and sedimentation is directly tied to strategy location and shape. When constructed breakwater islands are placed to protect a sandy beach, sediment deposition may occur in the low energy environment behind the breakwater island. Sedimentation rates are dependent on the local sediment longshore and cross-shore transport patterns. When placed to protect a harbor or to create a vessel passage from open to tranquil waters, sediment accumulation in the lee may need to be mitigated

As previously mentioned in Section 3.1, an often-applied metric for evaluating the hazard mitigation potential of CGI strategies is hydrodynamic quantity (e.g., wave height, water level) reduction. In the case of constructed breakwater islands, a wave transmission coefficient (the ratio of wave height offshore to that on the leeward side of the island) is often used to quantify the breakwater performance. Relatively speaking, the effects of crest elevation on the transmission coefficients are well documented for traditional breakwaters (e.g., USACE 1984, USACE 2002; Hardaway and Gunn 2010). Because of the advanced numerical and physical models, breakwater footprints, including location and shape, can be adapted to mitigate complex wave climates and embrace more innovative designs. The basic design parameters, such as segment gaps, segment lengths, and proximity to the shoreline, are still important. However, the existing empirical relationships among those parameters developed on the basis of implemented projects and natural landscapes (USACE 2002) can only be used for initial estimations.

Advanced computer models and physical models allow for more detailed assessments of complicated design of footprints and configurations to understand the impacts of design on both hazard mitigation and ecological benefits. A calibrated numerical model together with a physical model is a desirable approach to investigate the feasibility and effectiveness of such a strategy.

Ecological Benefits

The major benefits of this strategy are generated by transforming traditional intrusive breakwaters (typically concrete or large stones) into more natural barrier islands. This strategy can protect shorelines and provide socio-economic welfare to coastal communities. Ecological benefits are generated by the creation of habitat, including SAV, finfish, shellfish, sandy beach, and maritime or coastal marsh/shrub/forest lands, from shallow water to subaerial environments. Other environmental benefits resulting from the creation of various habitat types could include water quality improvement, greenhouse gas sequestration, and biodiversity improvement. These benefits are highlighted in Table 1.

The magnitude of these benefits depends on the size of a project, the size of each habitat type, and accommodated species. The value of each habitat type per unit area can be obtained from other strategies, e.g., constructed oyster reefs, living shorelines, and constructed wetlands. The value of the entire system could then be evaluated by quantifying the linkage and interaction between various habitats through pilot project studies. Neither the habitat unit value nor the combined value has been thoroughly studied.

In addition, this strategy requires a large volume of sediment; reuse of dredged material is one way to increase the project feasibility. A collaborative study reviewed the status of decontamination showing the evaluation and selection of advanced decontamination technologies (Stern et al. 2002). However, more recent studies were not found. The USEPA has documented options for Dredged Material Placement Decontamination Technologies. Prior to implementing this strategy, it is very important to develop the quality standards of soil placement for establishing healthy biota habitat and to explore suitable decontamination technology for NYC.

Drivers of Change: Failure Causes and Resiliency

A constructed breakwater island is a complex structure that can include one or more elements, such as beach, dune, marshland, maritime forest, and reefs. Each individual feature is vulnerable to various failure causes and therefore could contribute to the failure of the island as a whole, depending on a variety of storm or climate conditions. However, it should be noted that because this strategy creates a complex ecosystem, multiple types of redundancy exist, potentially making this strategy less prone to failure than some individual strategies.

To date, the lifespan of islands constructed from dredged material without engineering structures is not yet known, but it can vary significantly depending on where the island is located. Factors that may affect the sustainability (or failure) of this CGI strategy therefore are, first and foremost, the adaptability of the various habitat and ecosystem types within this strategy and the sediment stability of the strategy. The littoral sediment supply, the presence of engineered structures to retain nourished sediment, and the geotechnical and geochemical properties of dredged material used for the substrate are critically important. An appropriate maintenance and monitoring plan should be developed before a project is being implemented.

A case study conducted along the New Zealand coast showed that planting vegetation immediately above the restored beach can guide a sustaining beach-vegetation cycle and can promote the self-recovery process (Berg and Limited 2007). The plants that tolerate abrasive sand, high wind, and salt exposure survive in a fairly hostile environment and can promote sediment accumulation. The relationship of mutual support between vegetation and sedimentation remains dynamic and can be affected by external stressors. Either insufficient sediment supply or vegetation mortality due to storm or sea-level rise can cause damages to the system and result in collapse of the feature.

In a sediment-starved environment such as the New York Harbor, engineered structures (fences, sills, reefs, breakwaters) are critical to combat erosive forces and retain sediment. The breakwater islands for the Fort Pierce Marina, Florida, integrated a series of curved breakwaters and T-groins, which provide sediment nourishment. An understanding of the local sediment budget, including available sediment source sand sinks, is therefore needed in both planning for and designing any breakwater islands – in particular for the south shore of Staten island.

3.3.3. Unknowns and Data Gaps

The following unknowns and data gaps were identified by the research group for the constructed barrier island strategy. Many of the following questions can be addressed from studies related to other strategies, while some are meta-strategy questions, e.g., ecosystem value assessments across various habitats.

- How is the circulation pattern in the area affected by the project?
- How can we achieve consensus on project scale for this strategy? Can we anticipate an optimal project scale for specific objectives of habitat creation and survival?
- How are habitat values and hazard mitigation potential enhanced in a multi-strategy complex such as this strategy?
- What are the metrics to monitor the regional ecosystem, ecological communities, and various habitats? Can a rapid assessment tool be developed to assess net ecosystem benefits for a multiple habitats complex?

- Are there efficiencies in obtaining regional sediment budget, water quality, salinity, turbidity, wave climate, and water levels data for project planning?
- What are the regional and local sediment budgets for the NYC area? How can sediment transport models be improved to facilitate the implementation of this strategy? Where are suitable sediment borrow areas? How much sediment is available? What is the cost?

3.4. Channel Shallowing

3.4.1. Strategy Description

Channel shallowing is a strategy of reducing estuary or inlet depths to reduce the inland penetration of storm tides and can be a form of restoration in dredged systems that were historically shallower. In the case of a dredged system, a shallowed channel is a form of "restoration" and may promote the natural sedimentary system of tidal flats or wetlands. It could also improve wetland sustainability in the face of sea-level rise by providing a sediment source during storms or simply not providing a deep-water sediment sink that absorbs sediments that have been resuspended during the storm. Figure 5 shows a diagram of channel shallowing.

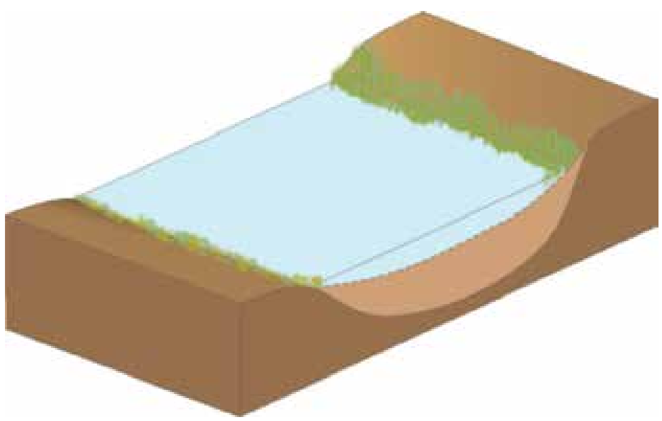


Figure 5. Diagram of channel shallowing (NYC DCP 2013)

This strategy is challenging and will likely be based more on economics and flood protection than ecosystem benefits. Channels were typically dredged for navigational purposes; there is typically an economic driver behind their maintenance. The cessation of maintenance dredging is referred to by the USACE as "de-authorization" and would require an economic assessment of tradeoffs. De-authorization may not be viable for large, high-traffic channels. However, one recent example exists of a shipping channel being de-authorized, in part because of a debate over whether it caused increased storm surge penetration. Dredging of the Mississippi River Gulf Outlet (MRGO) was de-authorized by the USACE in 2007, and the channel was physically blocked in 2009 (Shaffer et al. 2009).

3.4.2. An Update on the Status of the Science

The shallowing approach is a new concept, developed with attention to Jamaica Bay's Rockaway Inlet and two main interior channels, although it may have applicability to other channels and inlets in the region. The channels in Jamaica Bay were dredged deep and wide for shipping in the early 20th century, and archival research has shown that the average depth of the bay has increased from 1 meter in the 1800s to 5 meters at the present (Swanson et al. 1992), leading to higher tides and larger tide ranges (Swanson and Wilson 2006; Swanson and Wilson 2008). Hydrodynamic modeling has been used to show that shallowing Jamaica Bay's deep dredged channels would have reduced Hurricane Sandy storm tides by about one foot, and a combination of shallowing and extensive wetland island construction over much of the center of the bay would have led to a total reduction of 3 to 4 feet and a dramatic reduction in neighborhood flooding (Orton et al. in preparation). These experiments used an exaggerated shallowing to 6.6 feet maximum depth and were hypothetical scenarios designed simply to show the leverage shallowing has on flood elevations within the bay.

The method to be used for shallowing is an open question, and the strategy has not yet been used in this region. At one extreme, envisioned by Orton et al. (2012), shallowing could simply be initiated by decommissioning a dredged channel and allowing natural sedimentation to occur over a longer period of time, which would be a simple and potentially cost-effective strategy. At the other extreme, shallowing could be accomplished through direct sediment in-fill, similar to beach replenishment. However, for some systems like Jamaica Bay, this would require much larger volumes of sediment than beach replenishment.

A hydrodynamic modeling study of flood mitigation by natural shoreline features is presently underway for Jamaica Bay (Principal Investigators P. Orton, A. Blumberg, E. Sanderson, and K. MacManus), quantifying the impact of channel shallowing and wetlands on storm tides from a range of possible storms and on resulting flood zones (e.g., 100-year) for surrounding neighborhoods. An additional project is supplementing the study (Principal Investigators P. Orton, A. Blumberg, and J. Fitzpatrick), enabling researchers to also model structural flood protections (e.g., a surge barrier across Rockaway Inlet) and to quantify water quality and contaminant residence time impacts of all these adaptation options using a smaller set of storm scenarios.

Coastal Hazard Mitigation

Some basic aspects of bathymetric influences on storm surges or tides are at least qualitatively understood. Both tides and storm surge are "sea-level events" – events causing anomalies in sea level of varying durations, although surges are mainly forced waves and tides are periodic waves with a well-defined period and wavelength. Shallow (or narrow) channels at inlets and inside estuaries can reduce inland penetration of a tide due to a "bottleneck" effect of reducing the cross-sectional area of the channel and the resulting tidal prism (the amount of water transported in and out of a bay or estuary).

However, the detailed hydrodynamic effects of channel shallowing require further study and may be highly site or storm specific. There are locations where a shallowed channel might worsen flooding. For example, a reduction in the cross-sectional area of a river channel can slow the runoff of inland rainfall floodwaters, inducing flooding. Also, the time scale of the sea-level event, whether it be tides or a storm surge, also can influence its penetration into a bay or estuary – storm surges from cold-season storms (e.g., nor'easters) have a longer time scale, on the order of 1 day, and the bottleneck and frictional effects of a shallow inlet or channel may be lessened. A rapid sea-level event such as semi-diurnal tide or a fast-moving or small hurricane can have a time scale on the order of hours, and may be attenuated more strongly by a shallow inlet or channel (Aretxabaleta et al. 2014). A sea-level event like Hurricane Sandy's storm tide can be a combination of both types of events, with sea level rising for a few days (sometimes referred to as "forerunner surge") that penetrates into coastal embayments with little attenuation (e.g., Kennedy et al. 2011), followed by a rapid final sea-level pulse in the final hours.

Inside harbors and estuaries, there may also be opportunities for shallowing as flood protection, focusing on tide creeks that were once dredged for ship access to former port or industrial operations. Some tidal rivers have already shallowed due to natural sedimentation, such as the lower Hackensack River. The flood reduction that has already potentially occurred for areas surrounding these shallowed channels should be studied. Others tidal channels such as Newtown Creek are also possible candidates for study because they are pathways for flooding to enter into urban neighborhoods.

Very few studies have looked into the penetration of storm tides through a range of inlet and channel types, nor the intentional manipulation of their depths to mitigate storm tides. Due to this relative lack of prior research as well as the complexities listed above, numerical modeling studies are recommended for improving an understanding of the potential of channel shallowing for coastal hazard mitigation.

Ecological Benefits

The water-quality and ecosystem impacts of shallowing are also an area requiring further study because little is known at this time about these effects. The shallowing of an inlet could reduce the water exchange between the bay area and the open ocean, which could adversely impact the water quality inside the bay. To what degree the water quality will be affected for a given system should be studied in advance. An extreme example of the relationship between inlets and flushing is the breach on Fire Island, which has been shown to have improved water quality; closing this breach would likely eliminate the flushing of bay waters and eliminate this benefit.

Shallowed inlets or channels may increase the trapping of sediment inside a bay area, and thus stimulate vertical accretion of wetlands. It is possible that implementation of this strategy in Jamaica Bay may benefit wetland creation projects inside the bay. Baseline data including water quality, soil properties, groundwater table, and marsh species (growth) should be collected for impact control. Observations of vegetation growth and coverage are also important. It would be best to use remote sensing for data collection in a large two-dimensional extent; otherwise, it is costly to conduct a field survey in such a large region. Because this strategy largely relies on natural restoration after inlet fill, there is no specific habitat target. It will require more careful Before-After-Control-Impact (BACI).

Drivers of Change: Failure Causes and Resiliency

The strategy would be described as a failure if the shallowed channel is re-channelized due to natural flow (unstable cross-section) or if the channel shallowing poses overall negative impacts on the bay environment. Numerical studies can be utilized with an empirical relationship of tidal prism (the volume flux of water into and out of a system) and inlet cross-sectional area to predict the fate of a shallowed inlet and to determine the equilibrium depth of an inlet (Chen and Zhao 2008). Sea-level rise imposes instability on this strategy and may require maintenance to improve the channel depth toward a stable status. Understanding the stability of the inlet/channel requires tidal level records and the breaching potential during a storm event. Properties of existing sediment and fill-in sediment should be carefully reviewed for a stable construction of channel shallowing strategy. Ultimately, if channel shallowing promotes the ecosystem restoration, coastal resiliency will be improved and coastal defense enhanced.

3.4.3. Unknowns and Data Gaps

The following unknowns and gaps were identified by the research group for the channel shallowing strategy.

Hazard Mitigation Potential

- Are there existing de-authorized channels that have already naturally shallowed, and if so what has been the influence on flooding?
- What is the potential of this strategy for storm surge and wave reduction?
- What is the flood reduction benefit for this strategy for a variety of different flood events, from more common, annual floods to extreme cases like Hurricane Sandy or worse?
- What are the general channel and bay features (e.g., bay tidal prism, bay volume) that determine the capacity for channel shallowing to provide storm tide reductions?
- What is the influence of channel shallowing on erosion and accretion of islands or other features within the system?

Ecological Benefits

- What is the human and ecological value of this strategy, and how does it compare to the human value of the navigation channel that would be decommissioned?

- What are the general channel and bay features that determine the impacts of channel shallowing on water quality? What the differences in water quality and residence time between with and are without channel shallowing?

Channel Shallowing Feasibility and Resiliency

- What is the feasibility of shallowing a given channel, balanced against the utility of a channel for deep-draft vessels, in terms of all present uses of that channel, economic or municipal?
- Can we study the methods and time scales for shallowing a deep channel? What is the period of natural infill, based on present-day sediment transport?
- How does channel shallowing compare to berms, riprap, walls, and surge barriers in terms of long-term ecosystem and human resilience to flooding and sea-level rise?
- What are the effects of this strategy on the local sediment budget? How do bay and regional sediment budgets influence the stability of this strategy?

3.5. Ecologically-Enhanced Bulkheads and Revetments

3.5.1. Strategy Description

Ecologically-enhanced bulkheads and revetments are two types of shoreline armoring structures. They are linear, narrow features placed along the shoreline fringe with a vertical face (bulkhead) or sloped surface (revetment); incorporate rough irregular surfaces where organisms can colonize; integrate ecologically friendly materials and vegetation; reduce wave energy; and resist bank erosion. This strategy could be implemented as a brand new structure, or one could modify existing bulkheads and revetments to ecologically enhance them with biological elements and features. Figure 6 presents sketches of possible ecological enhancements.

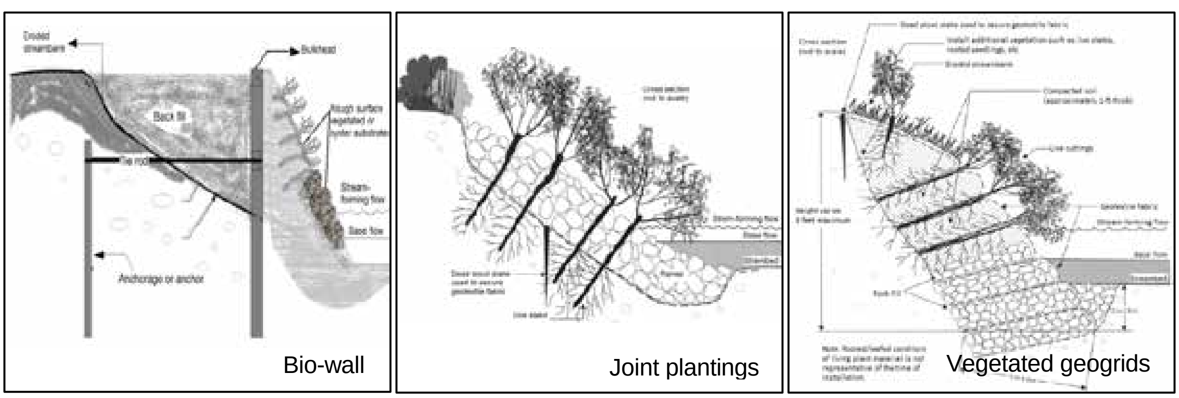


Figure 6. Photograph of an ecologically-enhanced bulkhead at Hunts Point Landing, Bronx, NY (HDR Engineering, Inc.) and sketches of other possible ecological enhancements.

Bulkheads and revetments are often used in urban areas, in marinas, and along rivers and coasts where space is limited. For instance, bulkheads are a common bank stabilization measure along the Hudson River. To limit the negative environmental impacts of these structures, without interfering with the structures' functional purpose, a variety of ecological enhancements can furnish important shoreline characteristics and improve habitat areas used by finfish, shellfish, birds, mammals, and other aquatic and terrestrial life. However, the design of such measures for a particular location must reflect a delicate balance between the required hazard mitigation and factors such as cost, aesthetics, and ecological services. Ecological enhancements for existing bulkheads include placing stones at the toe to provide shelter for finfish and aquatic life; hanging baskets to support marsh plantings at varying elevations along the face of the wall; and hanging units to decrease current speeds to encourage marine flora and fauna along the wall. Ecological enhancements for existing revetments include drilling small holes in the armor stones to hold water and develop habitat during periods of low tide; placing tide pools at mean sea level to retain water, increasing habitat and biodiversity; and planting trees in the voids between stones to increase soil stability.

Under certain circumstances, innovative techniques, such as live crib walls, vegetated geogrids, and tree/rootwad revetments, can be applied to provide protection and to create habitat as alternatives to bulkheads and revetments (Rella and Miller 2012). Each of these structures utilizes protruding vegetation, to slow current velocities, and stone and soil, to provide stabilization. Substituting these structure types is often limited by the necessity of a vertical wall for mooring vessels; the excavation of limited available land for the placement of structures with a larger footprint (e.g., vegetated geogrid or cribbing); or vulnerable and valuable property that requires the protection of traditional hard structures. Rella and Miller (2012) provides an overview of engineering approaches that have been used to manage erosion along sheltered shorelines, which are concentrated on but not limited to the HRE. Table 4 lists those techniques that can be used as alternatives to traditional bulkhead and revetments. They are displayed with respect to effects on hydrodynamics, sedimentation, primary ecosystem services, and vulnerability and resiliency. Three techniques, green (bio) walls, vegetated geogrid, and joint planting, which are shaded in Table 4, are the most applicable for ecological enhancements, retrofitting traditional bulkheads, and revetments. However, the ecological elements for each biologically engineered feature may not be appropriate for all sites and situations. For example, there can be problems with using vegetation and oysters because living creatures may fail to survive and grow. Vegetation is sensitive to soil type, water quality, and sunlight deficiencies. Shellfish may not survive and colonize the bio wall if water quality is poor. Plants may be uprooted by freezing and thawing, damaged by ice and debris, subjected to wave and current scouring, and trampled by wildlife and livestock. Careful selection of a strategy and its ecological components requires an understanding of the specific physical and ecological needs, including hydrodynamics, sediment patterns, bathymetry, and water quality. Therefore, design is location specific and requires extensive studies and data regarding the local environment. In-situ or laboratory experimental research and field observations are critical to implement a successful project. Site specific maintenance strategies are also required to ensure long-term project success (Allen and Leech 1997).

Table 4. Characteristics of ecological enhancement hazard mitigation measures

Hazard Mitigation Measures	Hydrodynamics			Sedimentation		Primary Ecosystem Services			Vulnerability and Resiliency	
	Flow resistance	Wave reduction	Wave reflection	Erosion control	Sediment trap	Natural appearance	Habitats provision	Access to water	Adaptability	Failure cause
Green (Bio) wall	○	○	●	●	○	●	●	○	○	Storm surge, waves, sea-level rise
Crib wall	○	◐	◐	●	●	●	○	○	◐	Moving ice and debris, sea-level rise, toe scour, rainfall
Live crib wall	○	◐	◐	●	●	●	●	○	◐	Moving ice and debris, sea-level rise, toe scour, rainfall
Wave screen	○	●	○	●	●	○	●	●	●	Ice and debris
Rootwad revetment	◐	◐	○	●	◐	●	●	○	◐	Flood, wave (overtopping), scour, sea-level rise
Tree revetment	◐	◐	○	◐	●	●	●	○	◐	Flood, ice, debris, sea-level rise
Jack field	◐	◐	○	●	●	●	●	○	◐	Strong current, sea-level rise
Geotextile roll	○	○	○	●	○	●	●	●	○	Scour, root wedging, ice and debris, sea-level rise
Vegetated geogrid	◐	◐	○	●	●	●	●	○	◐	Catastrophic storm waves rather than gradual hazards
Joint planting	◐	◐	○	●	◐	●	●	●	◐	Storm waves, sea-level rise

Note: ● Positive results – yes ◐ Positive results – some ○ Positive results – none

3.5.2. An Update on the Status of the Science

Among the potential biological engineered features, green (bio) walls, vegetated geogrids, and joint planting are emphasized in the following discussion as the most applicable ecological enhancement measures for bulkheads and revetments for the NYC area. More than 50 percent of coastal and marine infrastructure is made from Portland cement, a poor substrate for biological recruitment due to its highly basic alkalinity, leaching of toxic compounds into the water, and minimal surface complexity (Perkol-Finkel and Sella 2013). Habitats that do develop are typically less diverse than natural systems and are commonly dominated by nuisance and invasive species. By modifying the chemical composition or surface texture of coastal or marine infrastructure concrete, it is possible to improve its capability of supporting enhanced marine fauna and flora. The ecosystem services provided by enhanced infrastructure habitats include improved water quality, increased operational life span, improved structural stability, and mitigated hydrodynamic forces (Perkol-Finkel and Sella 2013). These services can be credited mainly to the natural process of biogenic buildup. Biogenic buildup is the deposition of calcium carbonate onto hard substances from oysters, serpulid worms, barnacles, corals, and other invertebrates creating valuable habitat for marine organisms. By lowering the high surface alkalinity of concrete from its normal pH of approximately 13 to 8 standard units (the average pH of seawater) and by texturizing or increasing the complexity of the surface, a more diverse recruitment and increased growth can be achieved (Perkol-Finkel and Sella 2013). A bio wall is a shear structure built on the substrate of bulkheads or gabions to provide ecological enhancement. Bio walls could incorporate terraced or roughened edges, utilize environmentally friendly materials, and introduce undulations along the length of a structure. A vegetated geogrid is a terraced wall consisting of alternating horizontal layers of soil wrapped in synthetic fabric with live branch cuttings throughout. Joint planting consists of adding live stakes or vegetation into the open spaces or joints of an existing riprap or rock-covered slope (Sotir and Fischenich 2007).

Coastal Hazard Mitigation

A bio wall is a transformation of a bulkhead that is meant for adding aesthetic and ecological functions. The potential protective values are limited to a slight reduction in wave run-up due to the surface roughness. The main protection function is carried over from the backbone structure, such as wave reflection and soil retention. However, because of the introduction of undulations, terraces, rough surfaces, and even vegetation, the impacts (especially negative) on the protection value of the transformed system need to be investigated so that the design of a bio wall can be intentionally guided.

Joint plantings and vegetated geogrids reduce flow kinetic energy, by the roughness and porosity of the vegetation layer, and can reduce current speeds during a stream high-water stage (Iowa Department of Natural Resources (IADNR 2006) and associated with tidal flows. A vegetated geogrid requires a large amount of soil fill and its performance depends on the vegetation species and soil properties. A developed vegetated geogrid bank is expected to be covered by branches which provide significant resistance. A joint planting is vegetated similar to a geogrid, but developed jointly with a riprap or rock-covered revetment. Live stakes can be randomly installed, with a density of roughly two to four stakes per square yard. Stakes have to be inserted into the soil underneath the rock-armored layer (IADNR 2006). The spacing of live stakes increases as the bank slope becomes steeper (Sotir and Fischenich 2007). The developed joint planting installation performs similarly to vegetated geogrids. The protection values are attributed to the vegetative resistance.

All of the discussed structures, except the bio wall, can create a tranquil environment at the lee (e.g., wave screen) or within the structure (e.g., vegetated geogrid), which leads to sediment accumulation and stream bank reinforcement. The main purpose of stream bank erosion control is thereby achieved by reducing wave energy or current speed at the shoreline, reinforcing the bank soil strength through root structures, inducing sediment deposition, buffering the abrasive effects of transported materials (ice and debris), and depleting pore water in the soil due to vegetation uptake (Klingeman and Bradley 1976; Gray 1977; Allen 1978). Figure 6 illustrates the structures of bio walls, joint planting, and vegetated geogrid.

While effective in minimizing gradual erosion, these measures are susceptible to event-based hazards, such as storm surge flooding during an extreme storm event. This strategy offers storm surge flood control only up to its crest elevation. The extent of flood protection provided depends mostly on the structure's elevation. The performance of the strategy will depend on project scale, ecologically-enhanced resistance, and changes in local climate (water levels, waves, and wakes). Perkol-Finkel et al. (2006) have proven that habitats exposed to stronger current regimes and increased mass-transfer accumulate more biomass. The disadvantage of being exposed to higher currents is increased shear stress on the surface of the habitat, which has proven to result in a decrease of the diversity of the species inhabiting the feature. Fixed habitats, which are placed along the shorelines of a body of water, where the slowest current velocities are experienced, are exposed to lower mass-transfer rates of water. Being exposed to fewer nutrients results in a decrease in the accumulation of biomass on the habitat; however, decreased shear stress does allow for more sensitive species to accumulate (Perkol-Finkel et al. 2006). Findings on effects of vegetation and oyster reefs on coastal hazard mitigation in other strategies can be, to some extent, applied here. Project-specific studies including field monitoring, physical models, and numerical models are necessary for design purposes. Herrington et al. (2005) applied scale physical models to test the impacts of implementing bio walls. Firth et al. (2014) suggests using native species diversity as an indicator to optimize the design and enhance the hardened structures.

Ecological Benefits

The ecologically-enhanced bulkheads and revetments are intended to improve the integrity of coastal ecosystem and enhance waterfront aesthetics. This strategy incorporates specific measures to attract and support both terrestrial and aquatic biota and to restore habitats. Aesthetically, they could also be designed to encourage access to the water and change the traditional concrete structure to a more pleasant natural landscape.

Two major ecological functions and benefits provided by ecologically-enhanced bulkheads and revetments are water filtration and habitat creation. Oysters on the bio wall surface are capable of sequestering chemicals, which improves water quality. Vegetated geogrids and joint planting create waterfront habitat for terrestrial wildlife, reptiles, and amphibians. Overall, these ecological enhancement measures improve aquatic habitat by providing food and shelter both in the riparian zone and coastal water. Sediment accumulation creates habitats for benthos and further traps carbon in the deposition.

Most likely, the ecological benefits of these strategies will not accrue until several months to 1 or 2 years after installation; therefore, the timing of initiation and project implementation is important. Furthermore, the extent of ecological benefits associated with ecologically-enhanced bulkheads and revetments is sensitive to the local environment and ecology. Prevalent vegetation species, slope of the bank, existing structure conditions, wave climate (wakes and wind waves), and current speeds are all important factors to consider in the design and appropriate placement along the waterfront.

Drivers of Change: Failure Causes and Resiliency

Designing an appropriate shore protection measure for a particular location reflects a delicate balance between the required human safety and factors such as cost, aesthetics, and environmental impact (Rella and Miller 2012). The primary cause of failure of ecologically-enhanced bulkheads and revetments is water surface elevations that are above the vegetation because few plants will survive when submerged. Washout of sediment as the floodwater recedes over the wall can also cause significant damage. Therefore, sea-level rise poses a considerable threat to the success and failure of these strategies. Where possible, to adapt to rising water levels, the bulkheads and revetments should extend higher in elevation. A bio wall tied to a bulkhead is not very adaptable to water level or other changing conditions after it has been built. Both joint planting and vegetated geogrids are adaptable in that an additional layer of stakes may be added to reach the desired elevation, until the elevation of the land behind the bullhead is reached. Because of the limited capability of self-adjusting to sea-level rise, design of this strategy should consider future sea-level change projections when possible, which requires accurate water level measurements, long-term trend analyses and an accurate understanding of vertical datum, which have been found erroneous for some locations. Improvement of those data is needed. Rella and Miller (2012) conducted a cost analysis comparing the economic value of traditional and alternative structures over a 70-year life span, considering the effects of two different sea-level rise scenarios. They concluded that living shoreline structures, despite their softer approach, were economically comparable to traditional structures. These living elements, under current conditions, improve the resiliency of the shoreline due largely to their ability to recover from moderate disturbances.

3.5.3. Unknowns and Data Gaps

The following unknowns and gaps were identified by the research group for the ecologically-enhanced bulkheads and revetments strategy.

Ecological Benefits

- How successful is an ecologically-enhanced structure in providing ecological benefits in addition to its traditional function of shoreline protection and stabilization?
- What are the metrics to monitor the regional ecosystem, ecological communities, and various habitats to demonstrate successful ecological enhancements?
- Are there any other ecological enhancement techniques that can be used to retrofit existing bulkheads and revetments?

Structure Design Guidelines and Resiliency

- How do wakes impact ecological enhancements and structure design?
- To what extent can vegetation stabilize the bank and structure?
- What is the stone size and depth of rock cover layer that is necessary for avoiding root wedging?
- If vegetation becomes overgrown, does it have an adverse effect on the shoreline?
- How does ice impact the living elements of CGI projects (both vegetation and animal life)?
- How guidelines are best improved for the design of coastal structures in icy environments?
- What effect does the growth of invertebrates on marine infrastructure have on the structural integrity of the material and its expected lifespan?
- Can ecologically-enhanced concrete and rough concrete surfaces increase the longevity and structural stability of hard coastal structures?
- How does the accumulation of biomass on marine infrastructure affect the amount of chloride penetration and maintenance requirements?

3.6. Living Shorelines

3.6.1. Strategy Description

For the purposes of this study living shorelines are considered soft shore stabilization treatments that are placed along the shore fringe; are designed with a mild offshore slope extending to shallow water areas; may include features such as constructed wetlands, sills, vegetated geogrids, vegetated cribbing, shallowing with sediment fill; form shallow, calm aquatic habitat; always incorporate vegetation; provide ecosystem goods and services, such as recreation, water filtration, and carbon sequestration; and mitigate erosive waves and stabilize the shoreline. An “ideal” living shoreline concept (CBF 2007) is shown as a complex of living plants, biodegradable material sills, oyster reefs, and/or offshore breakwaters. Living shorelines can be broad. In this study, the focus is on the sill-type living shoreline. Other types of living shorelines, such as living shoreline with constructed reefs, constructed wetlands, vegetated geogrid, are discussed in previous sections. The living shoreline strategy provides a natural approach for erosion control although it requires structural features to retain sediment and dissipate erosive waves attacking fragile shore. Traditionally, the structure is referred to as sills armoring for fringe marshes or wetlands that require a higher degree of protection. Figure 7 presents the typical concept and essential elements of a sill-type living shoreline.

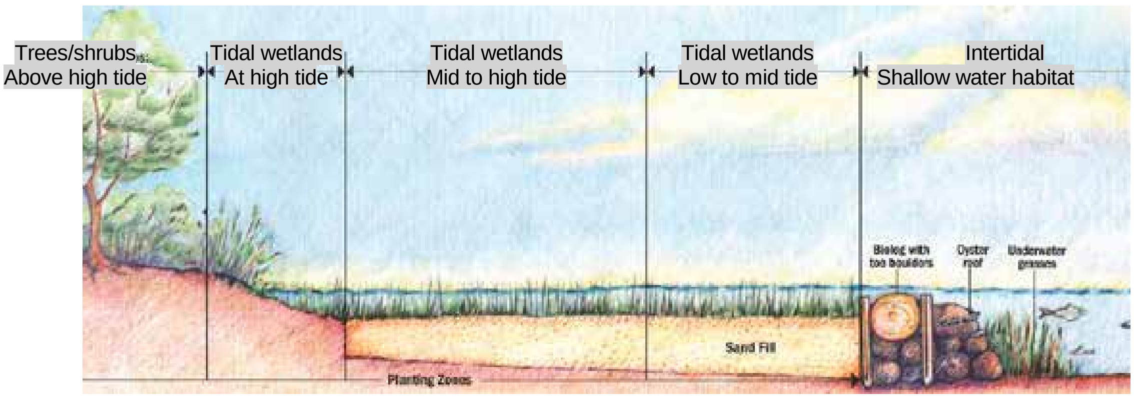


Figure 7. A sketch of living shorelines (CBF 2007)

Sills are low-elevation stone structures constructed in the water parallel to the existing shoreline. It is possible to create sills from a number of different materials, depending upon what materials are locally available and the desired type of habitat to be created or enhanced by the structure. There has been some work, including work by TNC in Georgia (TNC 2012), to try to use natural oyster recruitment as the cementing agent and zoned native plants to effectively stabilize shoreline erosion. These materials, including rock, armor stone, grout-filled bags, geo-tubes, and natural materials such as oysters and mussels, may be utilized to construct the entire structure (Rella and Miller 2012).

Sills dissipate wave energy, thus creating a tranquil environment. The tamed area of water lying behind the sill allows sand and sediment to accumulate between the structure and the shoreline. With time, this process can eventually raise the elevation of the bottom and create a perched beach given a sufficient sediment budget. This unique effect not only serves to further stabilize the shoreline or marsh behind the sill, but also replaces lost and eroded land. Often the area between the sill and the shoreline is filled during construction to accelerate the development of the perched beach and marsh plantings are added for stabilization, which further enhances the ecological goods and services of a living shoreline strategy, e.g., aesthetics, biodiversity, and recreation (Rella and Miller 2012). Sills, the only structural feature required by a living shoreline strategy, are low-lying, flexible structures that are less intrusive than traditional revetments or bulkheads with concrete units. This strategy allows the shoreline to retain many of its natural features, neither affecting the natural curvature of the shore nor the view of the stream bank or bay. Sills do not limit access to or from the shoreline for humans and animals. More importantly, sills can also be easily adjusted in height and width to accommodate any changes in water level due to rising seas (Rella and Miller 2012).

The flexible and small footprint of sills makes them desirable from an ecological viewpoint. Sills are limited to low- to medium-energy environments with a small to moderate tidal range. The smaller-sized stones used to construct sills are also susceptible to damage from ice during the winter or floating debris. The sediment that accumulates behind a sill is beneficial for marsh creation but can often result in the erosion of downdrift shorelines, as well as negatively impact nearshore SAV (Newell and Koch 2004). Due to a sill's ability to blend into the natural landscape, its presence must be clearly marked to avoid navigational hazards and human injury due to abrupt changes in slope and depth of the shoreline (Rella and Miller 2012).

3.6.2. An Update on the Status of the Science

Coastal Hazard Mitigation

The main purpose of this strategy is to mitigate shoreline erosion and degradation, which is often caused by gradual processes under general weather conditions and can be accelerated by acute events under stormy weather conditions. A stable living shoreline project promotes healthy marshland development. As a complex, the sill and the developed marshland reduce wave energy effectively. However, the quantity of wave reduction depends on the size of the sill, marsh width, marshland vegetation type, and the local wave climate. Potentially, tidal flooding and storm tide inundation can also be influenced because of the dense vegetation over the restored marshland. These energy and momentum dissipations are caused by resistance to the flow due to shallow bathymetry, rough bottom friction, and vegetal drag force. Details are provided in Section 3.1 "Constructed Wetlands and Maritime Forests". Performance metrics are listed in detail in Table 2.

Ecological Benefits

A sill allows for a significant amount of habitat to develop between itself and the shoreline. Often, sand and sediment will accumulate between the structure, and the shoreline can, in time, raise the elevation of the bottom and create a perched beach. This benefit serves to stabilize the shoreline or marsh behind the sill, as well as replace lost and eroded land. Two of the most common marsh plants used in the Northeast are marsh grass (*Spartina alterniflora)* and salt meadow cordgrass (*Spartina patens)* (Miller et al. 2014).

Spaces between the armoring stones and irregularity of shoreline curve can promote species richness and abundance due to the guarantee of water exchange and sheltered space, which can be used by fish and other marine organisms of varying sizes (Strayer and Smith 2000; Davis et al. 2006; Strayer 2007).

Properly designed sills with appropriate crest height and window spacing allows for circulation, preventing the water behind it from becoming stagnant. Circulation must also allow nutrients and harmful pollutants from upland sources, which normally enter the water during periods of heavy rain, to exit the area behind the sill in order to not negatively affect marine life.

Expected species include waterfowl and small mammals that feed on seeds from marsh plantings, invertebrates (fiddler crabs, snails, amphipods) that feed on organic matter in the soil, and fish that feed on organic matter of broken-down plant and animal material (Miller et al. 2014). If the sill structure is constructed from living components, such as oyster or mussels, the ecological benefits can be increased. Oysters have been described as a keystone species because they provide valuable ecosystem services for their habitats (Ravit et al. 2012). This colonial species form reefs that provide food and nesting habitat as well as sequester carbon, recycle biological material, and boost benthic productivity (Risinger 2012). Oysters can dramatically improve water quality by filtering water, reducing the turbidity of the water and the nutrient load, and increasing levels of dissolved oxygen (Ravit et al. 2012).. Sills are also desirable structures because they do not limit access to or from the shoreline for humans and animals. Sills may also be easily adjusted in height and width to accommodate any changes in water level due to rising seas.

Drivers of Change: Failure Causes and Resiliency

A sill is subject to the same modes of failure as any other sloping-front structures, such as breakwaters or revetment. If improperly constructed, the finer stones may wash out through the larger voids of the armoring, which could eventually lead to the deflation of the entire structure, lowering the structures' crest and compromising its effectiveness. Additionally, if the ground beneath the sill is not properly prepared prior to placement, the soil will sink due to the heavy weight of the stones. Washout and subsidence are progressive, slow-moving failure mechanisms, which can be avoided with proper design, construction, and maintenance. Scour along the front and ends of any stone structure is typical and continued erosion may result in the structure slumping or the stones moving. This will decrease the effectiveness of the structure but can be prevented with routine inspections. Historically, sills have been more commonly constructed in locations such as the Chesapeake Bay and Gulf of Mexico where ice does not need to be considered. However, ice must be considered in the design when constructing a sill in NYC. Floating ice, acting similarly to other types of floating debris, can apply large forces to the stones forming the sill and move them out of place. The movement of individual stones does not necessarily signal impending failure, but reoccurring damage will ultimately take its toll. Additionally, when ice becomes frozen to the structure, entire sections of the structure can be uplifted due to buoyant forces at high tide. In most cases, the damage to a structure due to ice freezing will cause a gradual failure (Miller et al. 2014).

3.6.3. Unknowns and Data Gaps

The following unknowns and gaps were identified by the research group for the constructed living shoreline strategy.

Hazard Mitigation Potential

- How effective are different sill materials (rock, gabions, bulkhead, living reefs) at dissipating waves and holding the front edge?
- How do marsh characteristics (elevation, plant density, width) influence energy dissipation?

Ecological Benefits

- What are the ecological benefits of living shorelines?
- How can edges be shaped to best enhance species richness and abundance?
- What are the metrics to monitor the regional ecosystem, ecological communities, and various habitats?
- What is the impact of living shoreline projects on water quality?
- How successful are living shoreline structures compared to traditional structural strategies in terms of hazard mitigation potential and ecosystem values?
- How do we integrate ecological benefits into project selection criteria?

Living Shoreline Design Guidelines and Resiliency

- What are the optimum sill dimensions (e.g., sill height, window dimensions, and spacing) for various estuarine/riverine conditions (e.g., channel shape, seasonal flow rates)?
- How do poor underlying soil conditions impact the long-term stability of living shoreline projects?
- How will sea-level rise impact living shoreline projects?
- How does ice impact the living elements of CGI projects (both vegetation and animal life)?
- How guidelines are best improved for the design of coastal structures in icy environments?
- How can knowledge regarding boat wakes be improved to aid and improve living shorelines design guidelines?
- How can present regulations be modified to allow for adaptive management of living shoreline projects?

4. Data, Conceptual Models, Monitoring, and Integration

The importance of data collection, handling, and management in the development and implementation of CGI cannot be emphasized enough. For any or all types of data, efficient monitoring, archiving, mining, and sharing are needed to improve efficacy. Because data collection can be both expensive and require considerable time and commitment of personnel, innovative ideas that leverage the efforts of others to minimize work and costs for the region are needed and could offer an improvement in the overall regional repository. Data could include field observations of various physical and ecological variables, laboratory experimental measurements, pilot project case studies, and numerical simulation results. The following subsections focus on the scope of existing regional baseline data, how data are collected, and how data are disseminated. The data discussed in this section include field observations and CGI projects implemented or proposed in NYC, which can serve as both baseline data and a knowledge base for future project planning and design.

4.1. Baseline Data

With respect to field measurements, baseline data are those used to determine the background environment where new services (e.g., projects) are to be implemented. The NYC coast is very diverse in both physical landforms and land use. As such, coastal hazards, ecological communities, and opportunities to improve coastal resiliency vary as well. Categorizing the baseline environments and understanding their physical conditions can facilitate better selection and design of CGI strategies. Drawing from previous waterfront planning and other regional efforts, this section documents the baseline environmental conditions in the NYC coastal region in the context of CGI.

The Urban Waterfront Adaptive Strategies study (NYC DCP 2013) identifies nine categories of coastal geomorphology based on the geologic landforms, shoreline conditions, and shoreline exposure to wave forces. The nine categories are combined into four types of shorelines here, ignoring shoreline reinforcement conditions, e.g., with or without engineered structure armoring features. Figure 8 shows them as (1) oceanfront beach/slope/plain; (2) marshlands; (3) sheltered bay slope/plain; and (4) sheltered bluffs. These types of shorelines are occupied by natural wetlands, beaches, hardened parking surfaces, piers, waterfront parks, industrial uses, and, in some cases, vacant land. The geomorphologic maps and land use maps of shoreline types, occupancy, and hazard exposure are presented in Part II of the Urban Waterfront Adaptive Strategies (NYC DCP 2013).

Shoreline areas are characterized by key environmental conditions and key ecological attributes. For instance, oceanfront shorelines encounter stronger waves than sheltered shorelines. Meanwhile, marshlands experience slower flow velocities than other types of shorelines. In addition to these physical conditions, ecological communities are representative at various shoreline environments. As a part of New York Natural Heritage inventory work, NYSDEC maintains a database of ecological communities representing the full array of biological diversity of New York State (Edinger et al. 2014). For instance, evaluation and classification of mudflat habitat values will be important to decide the placement of fill for coastal wetland construction. In Jamaica Bay, Kings County, and Queens County, there are marine intertidal mudflats which consist of quiet waters with organic matter and rich substrates. Building constructed wetlands in these areas will convert the ecological communities to salt marsh. A project that converts mudflats to salt marshes can be difficult to permit because mud flats are so limited in the region. A group of pilot projects set up to monitor and document changes in habitats and habitat values from existing mudflat habitats will be helpful to understand how ecological services change and what are the habitat tradeoffs. Therefore, data acquired and corresponding analysis can advise permission and regulation.

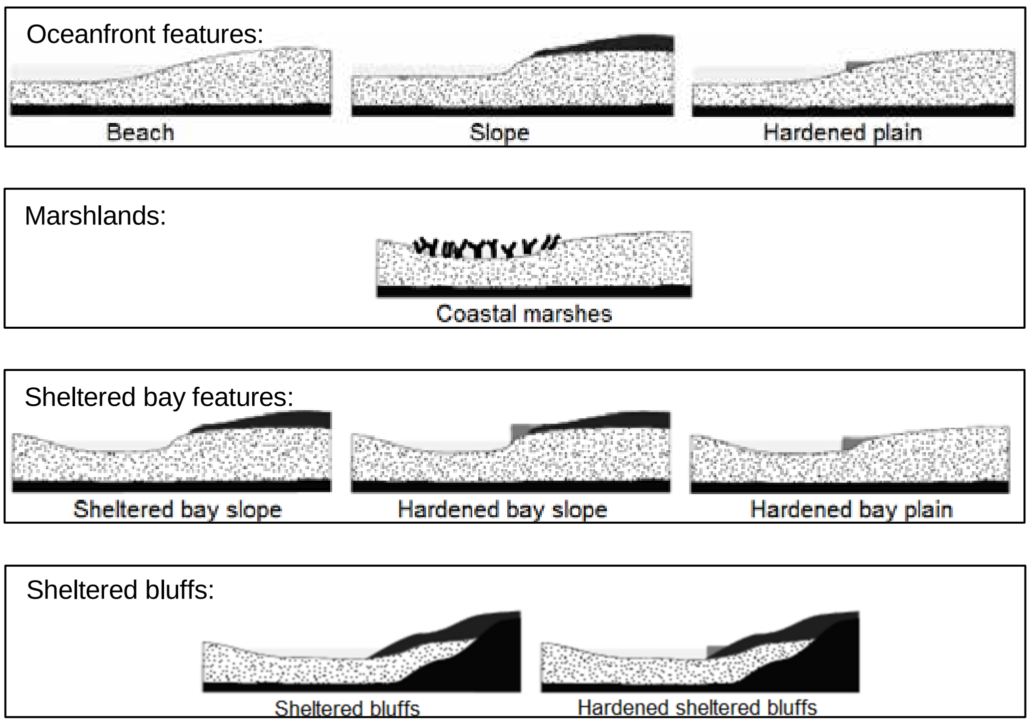


Figure 8. Geomorphology category

Tables 5 and 6 catalog data types used to gauge key environmental conditions and key ecological attributes. The corresponding metrics and potential uses of each category are included in the table. Prior to implementation of any project, some of the data listed in Tables 5 and 6 need be collected for a suitable time period in order to define baseline conditions; for instance, winds, water levels, currents, and waves (wind and vessel generated). These are the fundamentals of a waterfront environment.

Table 5. Environmental data inventory and metrics

Data Category	Metrics	Sources	Usage	Availability
Regional geology	Sea-level rise, subsidence, shoreline retreat	Literature, USGS, CO-OPS	Scenario design	Generally available
Regional geography	Bathymetry, topography	NGDC	Review of geographic features, model input	Digital Elevation Model (NYS GIS Clearinghouse)
Tides, storm surges, HWMs (station)	Water level fluctuation	USGS, NOAA CO-OPS, FEMA	Validation, surge reduction capability	NYHOPS; Tidal gages (most stations have no data); high water marks for recent hurricanes and storms
Water level (transect)	Water levels, distance	Literature, Survey	Long-period wave reduction ability	None
Waves (station)	Wave height Wave period	NDBC	Validation; wave attenuation capability; shoreline stability	NYHOPS; Wave data only at the moored buoy; no data available from NOS stations
Wake (station)	Wave height Wave period	Ad hoc network	Shoreline stability	None
Wave (transect)	Wave height Wave period Distance	Literature, survey	Decay coefficient regression	None
Current	Current speed	NOAA CO-OPS	Validation, circulation in harbor	NYHOPS
Winds (station)	Wind speed, direction	NCDC, NDBC	Driving force/wind model validation	Generally available
Wind field	Wind speed, directions	H*wind HRD/NOAA, wind model	Driving force	H*WIND dataset of Powell *et al.* (1996) Reconstruction from Holland (1980)

Data Category	Metrics	Sources	Usage	Availability
Sediment transport	Suspended sediment concentration, cross-shore and longshore transport rate	Field study	CGI strategy applicability and stability	Some
Sediment budget	Deposition rate; resuspension rate; sediment budget	Literature, Survey	Siting, project planning	Some
Bottom sediment	Grain size, mud fraction, consolidation, soil strength	Survey	Borrow pit	usSEABED database (Reid et al. 2005); NYCDPR ongoing project
Water temperature	Sea surface temperature (SST)	Survey, remotely sensed imagery	Oyster and other species survival	NYHOPS
Water salinity	Salinity (ppt)	Survey	Habitat development	NYHOPS
Water quality	DO, CDOM, phytoplankton, toxic chemicals	NYCDEP, Survey	Environment monitor, BACI	NYHOPS; NYCDEP
Vegetation roughness**	Drag coefficient, Manning's coefficient	Laboratory experiment	Validation, formula improvement, numerical model improvement	None
Flow over vegetated bed**	Flow velocity, water level, shear stress, vegetal drag	Literature, laboratory experiment, physical model	Validation, formula improvement, numerical model improvement	None
Ice sheet	Thickness	Observation	Shoreline structure stability	None
Float ice	Volume	Observation	Shoreline structure stability	None
** Vegetation is referred to as the prevalent species in the study area				

Table 6. Ecological data inventory and metrics

Data Category	Metrics	Sources	Usage	Availability
LULC	Land coverage classification	NLCD, CCAP, NACCS	Mask domain, habitat characteristics, project planning, roughness	NLCD (1992, 2001,and 2006); digital orthoimagery program
Vegetation morphological properties**	Height, diameter, density, brunches, foliage, aboveground biomass	Literature, survey	Estimation of roughness coefficient; habitat health condition	Some
Biomechanical properties**	Rigidity	Literature, survey	Estimation of roughness coefficient	Limited
Substrate properties	Shear strength (with and without plants roots), pH	Literature, survey	Project planning	Some
Vegetation habitats	% of species	Survey	Project planning; habitat evaluation	Some
Fauna structure	Species abundance, diversity	Survey	Project planning; habitat evaluation	Some
Wildlife	Bird diversity	Survey	Project planning; habitat evaluation	Some
Habitat diversity	Count	Survey	Project planning; habitat evaluation	Some

** Vegetation is referred to as the prevalent species in the study area

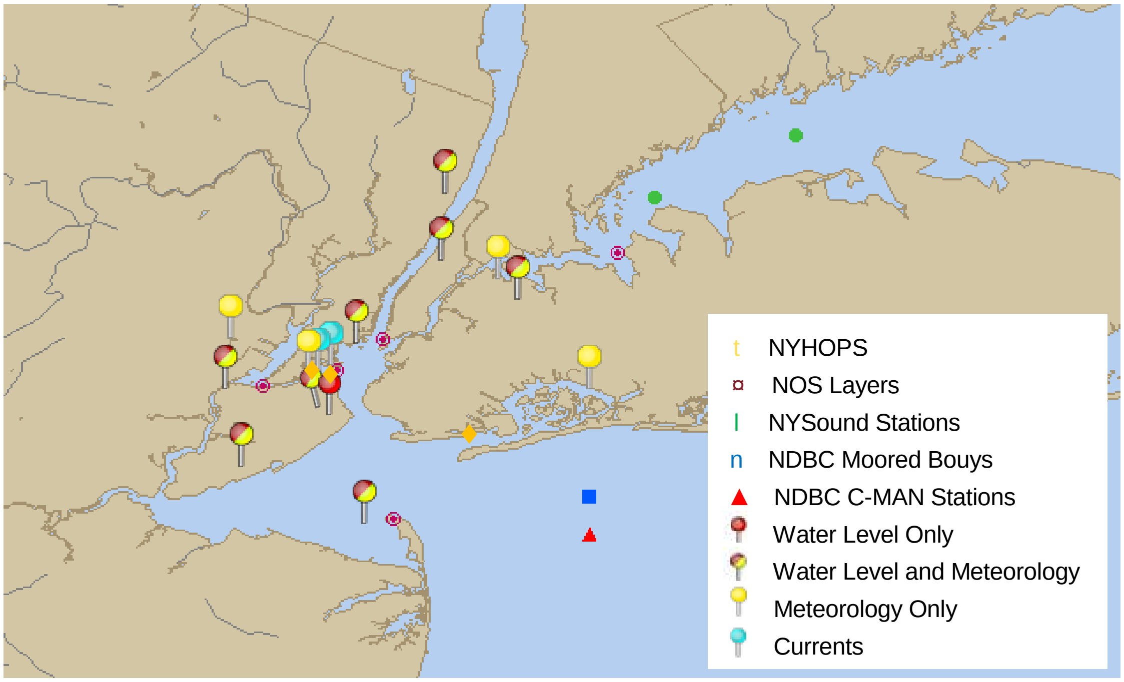


Figure 9. Observation stations

Typically, these data are measured at a meteorological or hydrologic station and reported at various sampling frequencies for a long time period depending on the operation history of a gauge or a meter. Lack of data or data accuracy increases uncertainties in project planning and design, which tends to increase costs. To illustrate, consider it is well known that different tidal level zones (supratidal, intertidal, sub-tidal) are comprised of different biotic groups (e.g., Edinger et al. 2014). As such, mean sea level and tidal levels are key parameters in designing shoreline-stabilizing CGI strategies, such as marsh-sill living shorelines and oyster reefs. Poor records of water levels would result in improper design or construction of the strategies, which can be costly in the design phase (e.g., additional survey and design changes) or after construction by damaging habitats and ultimately causing the project to fail.

In the New York Harbor area, some data monitoring stations are operated by federal agencies such as National Ocean Service (NOS), National Data Buoy Center (NDBC), and National Climatic Data Center (NCDC) (Figure 9). The station information and available data can be found on their websites. Other stations are Rockaway Inlet, ATON Gowanus 30, and Robbins Reef, New Jersey, from the regional observation system, the New York Harbor Observing and Prediction System. However, coverage of these stations is inadequate and data are rarely collected or published at most stations. The region could look to the northern Gulf of Mexico as a model for sharing data and monitoring where, since Hurricane Katrina (2005), the need for field measurements has received considerable attention. Wave and surge data collected during Hurricane Gustav (2008) are more extensive and detailed than for any previous Gulf hurricane. Agencies that collected data include NDBC, the Federal Emergency Management

Agency (FEMA), U.S. Army Engineer Research and Development Center (US-ERDC), academic institutions, and individual researchers (Dietrich et al. 2011; Kennedy et al. 2010). The lesson learned here is that adequate funding should be established for a long-term observation network and customized network for contingency (e.g., a storm event). Both event-based and long-term operational ad hoc deployments of instruments are necessary to improve existing observation networks and to ensure the accuracy of observed water level and its datum. Moreover, the action of collecting fundamental environmental data should be launched as soon as possible. But how can baseline data (water levels, vertical datum, salinity, dissolved oxygen, turbidity) be improved through funding mechanisms and data management to improve the probability of project success?

In addition to collecting environmental data for the waterfront, including water levels, waves and winds, water quality, sediment, and vegetation, it is very important to assess ecosystem response. The usSEABED database (Reid et al. 2005) provides data describing sediment and rock distributions in the waters off the United States and incorporates a wide variety of information about seafloor sediment, such as sediment texture, composition, and classification.

Harbor-scale or shoreline-scale information on seafloor sediment and geotechnical concerns would be useful for the siting and modification of in-water infrastructure. For example, a site with a hard bottom, as compared to a sandy bottom, can dramatically change the feasibility and type of in-water or living shoreline infrastructure. In NYC, usSEABED surficial sediment sampling covers mainly the Lower Bay and offshore region. The New York State GIS Clearinghouse archives and posts sediment data, such as sediment type, fraction, metal, and age in the HRE (Figure 10). A USEPA sediment quality study (Adams and Benyi 2003) conducted a second survey on bottom sediment in the NY/NJ Harbor area following a similar study in 1993 and 1994 (Adams et al. 1998). In Adams and Benyi (2003), there are 112 sampling stations in total (24 for each basin: Upper Harbor, Newark Bay, Lower Harbor [includes Raritan and Sandy Hook Bays], and Jamaica Bay). These datasets provide a good coverage of the NYC coastal area.

Sediment geotechnical properties are critical parameters to coastal resiliency. A recent 2-year study by NYCDPR collected data regarding salt marsh assessment at 24 salt marsh complexes, including soil strength tests. Additionally, TNC is coordinating a Marsh Elevation Network research project between the USFWS, USEPA, U.S. Geological Survey (USGS), and NYCDPR to estimate the shear strength of soils in Long Island, Jamaica Bay, Pelham Bay, and Staten Island marshes. A comparison and review of these data upon project completion would be beneficial to identify gaps where additional data should to be collected.

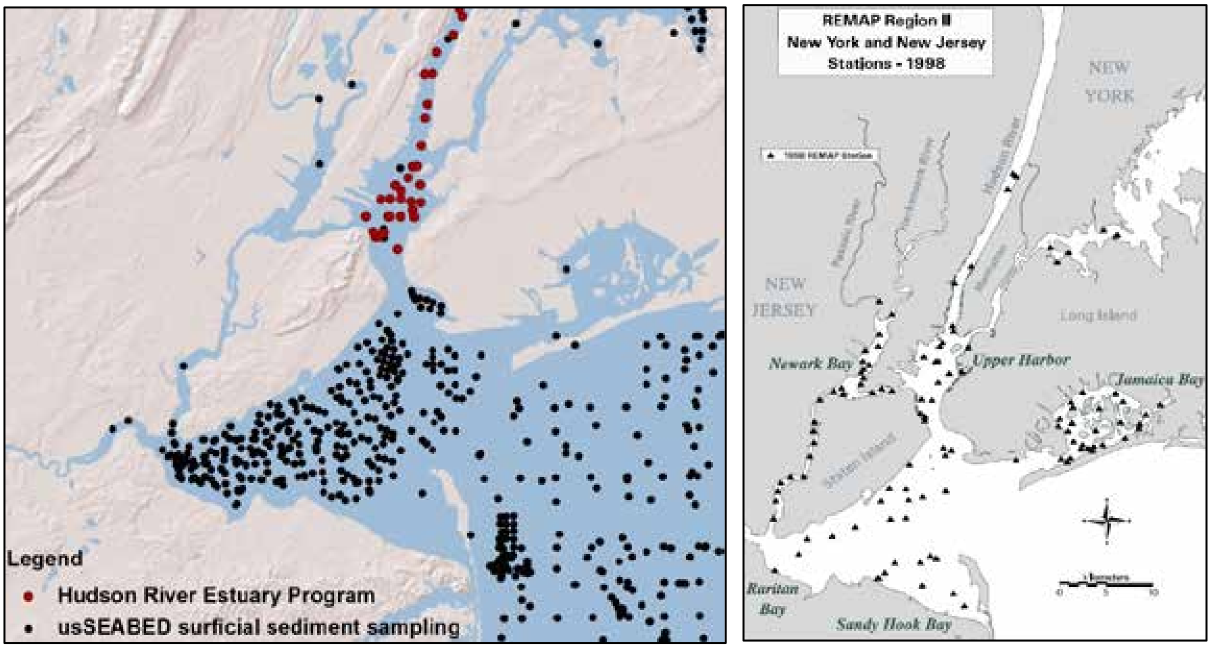


Figure 10. Illustration of bottom sediment sampling coverage. Left: usSEABED database (Reid et al. 2005) and HRE Sediment Map (Bell et al. 2005); right: USEPA sediment quality study (Adams and Benyi 2003)

It is recommended (or could be mandated) that additional data be collected from surrounding seafloor zones. Many studies related to dredging activity and dredging material up to year 2005 are cataloged by the Brooklyn National Laboratory (http://www.bnl.gov/wrdadcon/publications/articles/article.htm), including properties of sediments from the NY/NJ Harbor (Jones et al. 2002); sediment decontamination with beneficial use for the Port Authority of New York and New Jersey (Stern et al. 2002); and full-scale sediment decontamination applications (Stern et al. 2005). It would support harbor development should studies like these be carried forward in-depth, particularly if the monitoring and management of sediment properties, sediment quality, and sediment resources are integrated. A Regional Sediment Management Plan prepared under the sponsorship of the New York-New Jersey Harbor and Estuary Program (NY/NJ HEP) was released in 2008. Eight objectives and 45 recommended actions were presented, such as reducing sources of pollution, develop a sediment transport model and sediment budget, monitoring suspended sediment loading, and developing a dredge material beneficial plan. A sediment transport model was developed for the harbor (Miller et al. 2011) to examine the fate of sediment contaminants. Additionally, two ongoing projects funded through the Hudson River Foundation (HRF) focus on sediment transport, trapping and storage during extreme flow events (e.g. storms) in the Hudson River through numerical modeling and geological survey. The deliverables of these projects will improve the understanding of sediment movement and fate during high-energy event and provide more information about sediment resources in the Hudson.

Water quality, vegetation coverage, and biodiversity are documented on NYSDEC and NYSGIS websites. NYCDEP is responsible for the Harbor Survey Program, which collects water quality parameters, such as fecal coliform, dissolved oxygen, Secchi transparency, total suspended solids, and chlorophyll *a* (NYCDEP 2008). The Waterbody Inventory/Priority Waterbodies List (WI/PWL) Basin Reports provide narrative assessments of specific water bodies in each of 17 major drainage basins of the state, including the Jamaica Bay watershed and New York Harbor Watershed. However, coastal water quality is less frequently monitored, which is important to coastal ecosystem assessment.

Ecological Communities of New York State (Edinger et al. 2014) includes a comprehensive classification of both natural and cultural communities in the state. The classifications of ecological communities describe various systems from marine to riverine, aquatic to terrestrial, and wetlands to forests, including documentation of both vegetation and animal species. In addition, the national Gap Analysis Program (GAP) develops the data to support habitats and ecosystem conservation. Recent data developed by the New York Gap Analysis Project (NY-GAP; Smith et al. 2001) shows that more than 80 percent of the terrestrial vertebrate species within New York State can be found in the Hudson River Valley, extending from Albany to NYC. A subsequent, regional gap analysis project (Smith et al. 2002), focused on the Hudson River Valley (HRV-GAP). However, due to the limitation in field observations in the HRV-GAP, alternate analytical methods are recommended in order to increase the number and expand the pattern of field observations for each land cover type. These methods could include multi-temporal imagery along with a more robust image classification algorithm. This will improve our knowledge of landscape-level distribution patterns, leading to improved mapping and classification accuracies.

Because it is expensive to conduct field observations, use of remotely sensed imagery can be a cost-effective technique to generalize observations on a larger scale. Spatial resolution of imagery is critical to the level of accuracy, however, and while Landsat Thematic Mapper (which offers 30-meter resolution) is adequate for a regional environment application, the resolution may not be appropriate for a county or parcel-scale application. More intensive field validation in this case would be necessary. Collecting adequate land cover data and vegetation type is the key to defining the existing condition of the ecosystem during project planning and design to improve ecological services and reduce negative impacts.

The lack of up-to-date harbor-scale benthic habitat data limits the ability to plan for in-water strategies including CGI. When working on land, typically regional or city-scale land use or land cover (LULC) maps guide planning decisions. However, in the water, less information is available. Data on species biodiversity, density and species clusters, and distribution abundance would be very useful; otherwise, it remains difficult to assess the quality and location of benthic and seafloor habitat. Benthic data over time would support the siting and orientation of in-water structures, such as reefs and constructed breakwater islands. More detailed data would also help confirm the accuracy of the existing data and could support assessments of ecosystem evolution (e.g., develop and refine conceptual and ecosystem models). Additionally, these data will assist in the development of a list of priority species and habitats.

When considering siting and implementation of CGI, spatial data of high-value species and sensitive habitat locations and abundances are important. In Staten Island/Raritan Bay, the area south of Great Kills Harbor is designated as a shellfish transplant zone for hard clams, which is a valuable species for the Staten Island economy and ecology. However, to date, New York's maps (NYSDEC) show harvestable zones along the majority of the south shore of Staten Island, without details on whether and how many clams were present in these locations. The maps could be considerably more useful by including data on the relative abundance of clams or other such species at those locations. The New Jersey Department of Environmental Protection (NJDEP) publishes similar maps, which include abundance levels rated as low, medium, and high. Given the empirical correlation between species abundance and sediment type, as expressed through both clammers and landscape architects practicing in the region, this relationship should be studied and confirmed through systematic sampling of both sediment and clams. Existing data on sediment distribution and benthic data are limited in both resolution and accuracy. The development of a cross-state and cross-agency data collection plan and sharing platform would be highly beneficial.

Assessing changes in baseline conditions requires a well-defined network of sites from which to collect monitoring data over the long term. The cost of such programs, however, can be considerably high, particularly initialization. For instance, pilot projects should be carefully selected and a regional conceptual model (see next section) should define the data collection priority. A living, virtual laboratory of pilot projects utilizing various innovative strategies should be developed to systematically address hypothesis that require field observations and monitoring. Lessons and data collected through implementing and monitoring a pilot project could be used to create guidelines for future projects. Because pilot projects may be challenging to implement due to regulatory and cost considerations, it is recommended that pilot studies in the area be prioritized prior to implementation. What are the screening criteria for prioritizing applicable CGI strategies? Thorough review of existing data and projects is a first step towards building a catalog of different parameters and measures which can be effectively measured and integrated.

Metadata of case studies (initiatives and achievements) and projects are important baseline data. Data from case studies, including project location, motivations, goals and objectives, designs, implementation, post-project maintenance, monitoring, and evaluation, and pilot projects can be critically important to the planning and design of new CGI projects. Collection and classification of implemented projects can assist in decision making and adaptive management. Accordingly, management and data dissemination are important. Examples can be drawn from the experience of the European Portal for Integrated Coastal Zone Management project, OURCOAST. Similarly, the HRNERR also has a database of some demonstrative pilot projects of sustainable shorelines (HRNERR.org). This can be a good regional example and could be further expanded to include the coastal regions in NYC. Table 7 summarizes potential project monitoring locations in NYC that could be used in a demonstration network to further the monitoring and metadata available and to provide other "answers" to the unknowns of project performance and hazard and ecosystem response.

Table 7. Potential project monitoring locations

Project type	Project name	Project location
Maritime forest and coastal wetland restoration	Great Kills Marsh	Great Kills, Staten Island south shore
	Sunset Cove	Located west of Cross Bay Boulevard between West 19th and West 22nd roads
	Spring Creek North	North of the Belt Parkway, between Fountain Avenue, and 157th Avenue, located in Northern Jamaica Bay
	Spring Creek South	South of the Belt Parkway, on the east side of Spring Creek, located in Northern Jamaica Bay
	Alley Pond Park NE	The park is between Northern Boulevard and the railroad, east of Alley Creek
Breakwater	Plumb Beach Breakwater	Plumb Beach in Brooklyn along the Belt Parkway
	Great Kills / Crescent Beach Breakwater	Great Kills and Crescent Beach are located on the south shore of Staten Island
	Tottenville Living Breakwater	Tottenville is at the southernmost section of Staten Island south shore
Oyster reefs	Oyster Restoration Research Project	Bay Ridge Flats, Governors Island, Hastings, Soundview and Staten Island
Ecologically-enhanced bulkheads and revetments	Harlem River Park	Between Harlem River Parkway and the Harlem River
	Hunts Point Landing Salt Water Restoration	Bronx, NYC, New York, located along the East River at Farragut Street
Living shoreline	NA	NA
Channel shallowing	NA	NA

4.2. Conceptual Models

A system-wide conceptual model is a promising planning tool to direct monitoring demands and necessity. Gross (2003), in the National Park Service (NPS) Inventory and Monitoring Program, emphasizes that conceptual models are a key element of environmental monitoring programs. Conceptual models can be “used to develop, refine, and document a common understanding of ecosystems” (DRERIP 2010) and must be able to integrate our current understanding of system dynamics and identify important processes, key ecological attributes, and indicators. They should illustrate the connections between indicators and ecological states or processes, facilitate communication of complex interactions, synchronize the current status of data availability, and isolate needs of new data or metrics, from which project managers or agencies can recommend an appropriate data collection plan. Well-constructed conceptual models provide a scientific justification for the choice of indicators and framework for the monitoring program. Development of conceptual models needs collaboration and common goals; need to know what targets are, how do rank and prioritize them, and what are the path forward.

A set of conceptual ecological models has been developed for South Florida restoration as a framework for supporting integration of science and policy. The system is composed of eleven ecological conceptual models in major physiographic regions in South Florida, one Total System Model for South Florida, and one international regional model. These conceptual models are key components of an Adaptive Management Program, which was developed for the Comprehensive Everglades Restoration Plan and are being used as planning tools to guide and focus scientific support. Development of the conceptual models aided in consensus building among scientists and managers regarding the set of working hypotheses that explain the sources and effects of major anthropogenically induced changes in the natural systems of South Florida. Similarly, conceptual models have been developed for the Sacramento-San Joaquin Delta in California and for coastal protection and restoration in Louisiana (Peyronnin et al. 2013). In California, the Delta Regional Ecosystem Restoration Implementation Plan (DRERIP) conceptual model supports an evaluation tool for ecosystem restoration as well. The Louisiana's Coastal Protection and Restoration Authority integrates coastal restoration and hurricane protection by marshaling the expertise and resources of the Department of Natural Resources, the Department of Transportation and Development and other state agencies, to speak with one clear voice for the future of Louisiana's coast.

What are the considerations for the development of an NYC-specific conceptual model which can integrate cross-agency needs and interests? Is it necessary or reasonable to divide the harbor area into subdivisions regionally and/or to create individual conceptual models for unique ecological communities, such as a conceptual model for coastal wetlands only? How should hazard mitigation, ecosystem restoration and coastal resiliency be integrated in conceptual models? What are the coastal resiliency and protection targets that should be identified in a conceptual model (e.g., wave reduction, reduced structure count in the floodplain, reduced structure count in high wave zones, etc.)? There are a couple of collaboration programs, such as SIRR, Comprehensive Restoration Plan (CRP) for NY/NJ Harbor Estuary, and the New York Rising Community Reconstruction Program (NY Rising). How can those programs be refined or modified to incorporate both large scale drivers and local-scale stressors? USACE is revising CRP to incorporate post Hurricane Sandy studies, to include restoration opportunities and implementation of projects under both a hazard mitigation and habitat restoration mission, and to add coastal reference monitoring system priorities. Can CRP be adapted to become a regionally accepted conceptual model for both hazard mitigation and ecosystem evaluation of CGI strategies? It is anticipated that a regional conceptual model for NYC region should include cross-agency goals, monitoring needs and a long-term management plan.

4.3. Monitoring

With the guidance of conceptual models, monitoring program(s) can be designed for collecting both baseline data and specific ecosystem changes. Some monitoring programs have been developed for the Hudson River watershed, but the coverage and spatial resolution specific to the New York Harbor are scarce and limited.

The Coastwide Reference Monitoring System (CRMS) in Louisiana is a successful case study that is operated by the Louisiana Coastal Protection and Restoration Authority in conjunction with the USGS. CRMS was developed to meet the needs of collecting data for the coastal protection and restoration efforts and funded through the U.S. Congress enacting the Louisiana CWPPRA program. In coastal Louisiana, it is difficult to find comparable test sites; therefore, a multiple reference approach using aspects of hydro-geomorphic functional assessments and probabilistic sampling was adapted into the CRMS design (Steyer et al. 2006). The CRMS approach gathers information from a suite of sites that encompass a range of ecological conditions across the coast (Steyer et al. 2003). Trajectories of changing conditions within the reference sites can then be compared with trajectories of change within project sites. The CRMS design not only allows for monitoring and evaluating the effectiveness of each project, but will also support ongoing evaluation of the cumulative effects of all CWPPRA projects throughout the coastal ecosystems of Louisiana.

Reef Check California (RCC) is another monitoring program that concentrates on reefs along California's coast. The program is building a network of informed and involved citizens who support the sustainable use and conservation of California's nearshore marine resources. Volunteers are training to become citizen-scientists to survey nearshore reefs and generate data on the status of key indicator species. Surveying efforts will not only fill gaps in the state's existing marine monitoring network, but will allow interested parties to contribute valuable ocean knowledge to the management process (Freiwald et al. 2013).

Although CRMS was developed to mainly monitor coastal wetlands and RCC was developed for a coastal reef system, experiences in design and operation from both programs, (e.g., design of a monitoring and data sharing network, multi-reference approach, and citizen-involvement strategy) can aid in the development of an NYC system-wide monitoring program. Programs like these are worth exploring in-depth. In addition to traditional programmatic or project based monitoring efforts, it is recommended that a committee of scientific, agency, and local residents (especially experienced fishermen and clammers, etc.) discuss and guide sampling locations, frequency, method, species, and key parameters in one or two workshops; a panel of scientific experts should then review the draft protocol to ensure that the sampling design and methods and data collection categories are both scientifically sound and feasible. For instance, how feasible would it be to develop monitoring programs to improve benthic habitats mapping? Field testing is recommended for quality assurance and quality control. Field testing can be conducted in some developed pilot project sites for each CGI strategy or corresponding ecosystem.

The Interstate Environmental Commission (IEC) has initiated a shared-waterway group to facilitate communication between state, nationwide, and local partners and agencies for monitoring related activities. One of the deliverables IEC is working on is to create an inventory of monitoring program activities, data gaps, and efficient ways to expand monitoring in the region. IEC's ongoing efforts may be a good foundation to explore a framework for obtaining, archiving and sharing environmental baseline data. Additionally, the Hudson River Environmental Conditions Observing System (HRECOS) is an established program that could be a foundation for future monitoring in NYC. It can extend to cover the New York Harbor area. With the guidance of a conceptual model and monitoring protocol, HRECOS or a similar program can be developed to encompass:

- Sub-plans of data monitoring for each project or new site;
- Synchronization of collected data to avoid duplication; and
- Attention to data categories of scarcity.

Another essential goal of monitoring is to ensure project stability and sustainability. This type of monitoring is at a project scale and is often short term depending upon monitored variables. There is not a consistent maintenance plan for various CGI strategy projects; however, it is recommended that a plan be developed that includes regular inspection of structure stability (scouring, stone weathering, etc.) and ecological element survival (plants spreading, oyster survival and growth, etc.). Any monitoring plan should have an adaptive management plan that updates monitoring priorities and keep baseline data, project data and scientific findings at the same line. As is discussed in the next section, data collected for all individual projects should be "ported" to a single platform to drive consistent data formats and sharing.

4.4. Integration

Funding availability is often a bottleneck for monitoring and data collection. This is particularly challenging when funding for long-term observations, as well as contingency funds for episodic events like high-intensity storms, are necessary to advance the understanding of CGI strategies. Demonstration of high data usage and efficient data collection is important for continuous receiving funding.

Data integration for effective dissemination is a necessary step to promote efficiency of data acquisition and application. With a centralized virtual database for observational data and metadata, one can easily identify data sources and gaps, avoiding extra field work or duplicated design of data collection plans which would save money and time for other enhancements. Publication of field data or reports to a virtual database should be encouraged through funding policies in order to share information and reduce costs. For example, many stations in the coastal area of the Gulf of Mexico operated by local agencies share collected data with the national observation network, e.g., WAVCIS (Louisiana State University Wave-

Current-surge Information System), LUMCON (Louisiana Universities Marine Consortium), and DISL (Dauphin Island Sea Lab).

For NYC, it is recommended to develop a web portal that makes data more widely available and accessible in this area. The portal would include environmental or ecological data, field observations, remote acquisition data, and surveyed or processed data. This portal would not have to be a data repository itself; however, it would provide at least the metadata to what is available along with the associated links to the data sources. For the data that are readily available, such as observations from the NOS (a division of the National Oceanic and Atmospheric Administration) stations, a background retrieval and format conversion can be programmed to improve the convenience of data use. It requires identification of commonly used data formats for each measured quantity. This web portal can be maintained by a government agency, such as NYSDEC, NYSDOS, or an academic institute. These data can be updated at both planned intervals as well as on a project-by-project basis. Future monitoring plans can be posted in the portal. A portal similar to Harbor and Estuary Programs OASIS portal, which tracks restoration and habitat improvement projects throughout NYC and New Jersey (http://www.urbanresearchmaps.org/crp/map.html), is recommended.

This integration framework can be initiated as a research consortium, which is then followed by specific monitoring plans to fill gaps. Louisiana, Mississippi, and Alabama have formed the Northern Gulf Coastal Hazards Collaboratory (NG-CHC), a consortium to leverage their partnerships, proximity, and prior investments to advance the science and engineering of coastal hazards across the tri-state region and to address issues of national importance including coastal system response, risk management of coastal hazards, and the sustainability of economically important coastal fisheries, marine transportation, energy development, and strategic national defense. This project is funded through the National Science Foundation. One of the project strategies is to use a service-oriented approach to help integrate regional data providers into a distributed data management system in support of the community modeling framework of NG-CHC. Although this data integration mainly serves for coastal modelers, the concept of integrating data providers and unifying data formats for re-distributing is recommended for data integration in the NYC area. Strategies that enhance dissemination and sharing of data could advance the communities' collective understanding of CGIs in the region by supporting the monitoring and evaluation of performance and response of projects and thereby reducing uncertainties.

Similar to NG-CHC, the recently formed Science and Resilience Institute at Jamaica Bay (SRI@JB) is a partnership of the NPS, the City of New York, and a consortium of nine research institutions. Each of the nine research institutes offers a range of relevant science and education assets and linkages to Jamaica Bay. Would it be possible for this institute to expand and cover the New York Harbor area? How could this institute serve to integrate data in the region? It is clear that it is necessary to create or designate an organization to initiate the data integration framework and leverage investments to increase baseline data volume and to advance the understanding of baseline conditions and potential changes. The development will require discussion and collaboration among agencies and multiple states. This work should follow the development of conceptual models and monitoring programs, but should not be developed in isolation from those efforts.

5. Meta-strategy Research Plan

Building upon the data gaps and unknowns in the literature and data gaps review, the following research agendas and tasks have been developed to improve our understanding of CGI. The research plan is broken into two groups, Meta-strategy Research Plan and Strategy-Specific Research Plan. The Meta-strategy research plan includes tasks that will benefit all CGI strategies in NYC, e.g., data monitoring plan, data integration platform, which are concentrated in this section. The Strategy-Specific Research Plan is presented in Section 6, including tasks that target individual CGI strategies and improve the understanding of how CGI strategies provide hazard mitigation and habitat values.

All research tasks are ranked according to their impacts on four categories, with each category rating ranging from 0 to 3:

- **Fundamental Principles**: defined as the fundamental science behind the evaluation of CGI strategies. These principles are generally not NYC specific, but critical to understand prior to further evaluation at a city or project scale. This category weighs 1 or 0 suggesting that the understanding of fundamental principles would be improved notably or marginally.
- **Chronology:** defined as the dependency of projects on others. A rating of 3 for this category suggests that the agenda item can/should start right away, requiring no other up-front projects or little initial cost. Otherwise a lower score would be assigned.
- **Regional Applicability:** defined as the local environmental characteristics and data relevant to NYC. A rating of 3 for this category suggests that the understanding of NYC-specific topics and/or the quality and coverage of data would be notably improved.
- **Affordability:** defined as the range of project costs. A rating of 3 for this category suggests that the agenda item is relatively affordable (e.g., desktop studies), whereas a rating of 0 or 1 is given to projects that may be expensive in nature (e.g., pilot and field studies). Note, affordability does not account for construction costs.

Summation of the ratings of all four categories gives an overall rank ranging from 0 to 10. A task with the highest score is highly recommended.

Note that no research agenda items have been specifically identified for the constructed breakwater islands strategy. A breakwater island can be considered as a functional combination of an artificial island or reef and a breakwater and the value of each habitat type per unit area can be obtained from other strategies, e.g., constructed oyster reefs, living shorelines, and constructed wetlands. Research questions pertinent to constructed breakwater islands are addressed as part of the research agenda items for other strategies and meta-strategy items.

Agenda 5.1 Conceptual Models and Monitoring Protocols Development
Motivation
A conceptual model can be used as a platform to drive collaboration amongst agencies in the region. Conceptual models illustrate the connections between indicators and processes (ecological and hazards), facilitate communication of complex interactions, synchronize the current status of data availability, and isolate needs of new data or metrics, from which project managers or agencies can recommend an appropriate data collection plan. Well-constructed conceptual models provide a scientific justification for the choice of indicators and framework for the monitoring program. Development of conceptual models needs collaboration and common goals; need to know what targets are, how do rank and prioritize them, and what are the path forward. For instance, a set of conceptual ecological models were developed for South Florida restoration as a framework for building scientific understanding and a consensus among scientists and managers regarding the set of working hypotheses that identify specific, large-scale stressors, ecological effects of these stressors and ecological linkages between stressors and key attributes of the natural system. The Louisiana Coastal Protection and Restoration Master Plan integrates hazard mitigation potential to traditional coastal restoration missions, enhancing coastal resiliency. Experiences from those efforts demonstrate the importance of developing conceptual models and starting active cross-agency communications. In the NYC region, there are existing collaboration programs, such as SIRR, CRP, and NY Rising. How can those programs be refined or modified to incorporate both large scale drivers and local-scale stressors? How can a set of conceptual models integrating hazard mitigation and habitat restoration be established to effectively direct monitoring needs, scientific studies and shoreline management? Some monitoring programs have been developed for the Hudson River watershed, but the coverage is sparse for NYC and the collaboration is loose. Development of a monitoring protocol for the harbor is important, so is a framework coordinating monitoring efforts and uniting research forces. A system-wide conceptual model is a promising planning tool to direct monitoring demands and research necessity for a natural system, which should be developed for the NYC area. Development of the system-wide ecosystem conceptual model and a set of sub-scale conceptual models should consider whether it is necessary or reasonable to divide NYC into subdivisions (e.g., the Hudson River watershed and New York Harbor). Considerations may also include whether ecological community conceptual models should be developed, such as a conceptual model for coastal wetlands only. These conceptual models are non-quantitative planning tools that support integration of science and policy. They should illustrate the connections between indicators and ecological states or processes, facilitate communication of complex interactions, synchronize the current status of data availability, and isolate needs of new data or metrics, from which project managers or agencies can recommend an appropriate data collection plan.

Agenda 5.1 Conceptual Models and Monitoring Protocols Development
Key questions
The following research questions have been identified. Section headings are annotated to indicate where questions originated. · What are the considerations for the development of an NYC-specific conceptual model which can integrate cross-agency needs and interests? (4.2) · How to improve the existing monitoring network for obtaining and sharing better/complete environmental baseline data? (4.4) · Can CRP be adapted to develop an accepted cross-agency conceptual model for NYC region? If yes, which elements of a conceptual model for hazard mitigation and ecological assessment are missing in the CRP? What aspects need to be improved? (4.2) · What are the metrics to monitor the regional ecosystem, ecological communities, and various habitats? (3.1, 3.2, 3.3, 3.4, 3.5, 3.6, 4.1, and 4.3) · How can we evolve/update monitoring protocol best as the state of the science evolves? (4.3) · What are the metrics to quantify the hazard mitigation performance? (3.1, 3.2, 3.4, 3.6, 4.1, and 4.3) · How can monitoring programs help improve benthic habitat mapping? (4.1, 4.3) · How can baseline data (water levels, vertical datum, salinity, dissolved oxygen, turbidity) be improved through funding mechanisms and data management to improve the probability of project success? (4.1) · How to quantify/qualify each project and to identify its role in the system? (4.2) · How to define control sites to benchmark ecosystem values for project(s)? (3.1,.4, and 4.3) · How can advanced techniques, e.g. remote sensing, be best used to support regional data acquisition? (4.1, 4.3)
Research tasks
1. Evaluate existing programs, such as CRP, SIRR, and NY Rising, to identify critical components that can be adapted to develop a NYC area conceptual model (likely composed of models at various levels) for both hazard mitigation and habitat restoration. a. Review and comparison of existing programs b. Develop cross-agency goals of the conceptual models and specific objectives c. Identify missing elements in existing programs to achieve the cross-agency goals d. Develop conceptual model at different levels (e.g., see the example framework in the

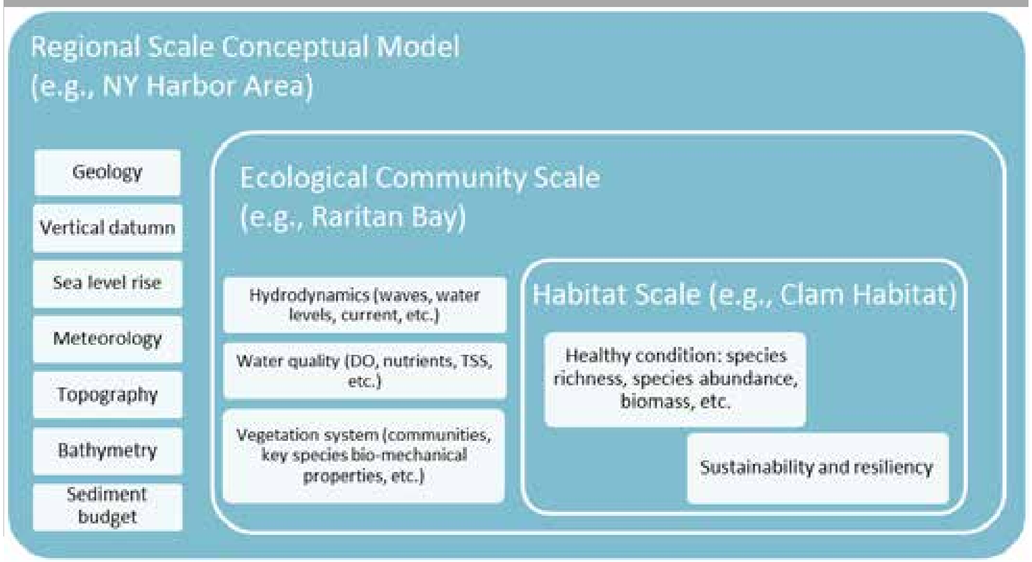
Agenda 5.1 Conceptual Models and Monitoring Protocols Development

figure below, which includes a variety of scales and data considerations)

i. Regional scale
ii. Various eco-communities (e.g., estuarine, riverine)
iii. Various habitats (e.g., salt marsh, oyster reefs, benthic)
iv. Hazard mitigation solutions may be included in either a community scale model or a habitat scale model

e. Include guidance for developing monitoring framework
f. Illustrate feasibility of applying the models for NYC region
g. Include considerations of developing adaptive management plans

Example framework of conceptual models



Qualified personnel	Ecologist; Coastal Engineer; Planner			
Ranking	Fundamental principles	Chronology	Regional Applicability	Affordability
	(0)	(2)	(3)	(2)
Overall ranking	(7)			

Agenda 5.1 Conceptual Models and Monitoring Protocols Development

2. Identify and test metrics to monitor characteristic ecological communities and habitats including the identification of control sites as benchmarks.
    a. Review metrics proposed by previous studies (e.g., those proposed by TNC and NWRs) to determine applicability for NYC
    b. Propose updated NYC-specific metrics to consistently evaluate ecological benefits across various CGI strategies and NYC regions and to determine whether projects will meet design targets and compare performance across projects
    c. Explain how to use the metrics, how to define/select control sites for testing the proposed NYC specific-metrics and benchmarking project performance
    d. Establish a process for adding or removing parameters as the state of the science changes
    e. Describe recommendations for monitoring protocol development (Task 5.1.3)

Qualified personnel	Biologist; Ecologist; Planner; Coastal engineer			
Ranking	Fundamental principles	Chronology	Regional Applicability	Affordability
	(0)	(3)	(3)	(3)
Overall ranking	(9)			

3. Develop monitoring protocol for collecting ecosystem data
    a. In coordination with Task 5.1.2, and by working with varies agencies and stakeholders, prioritize the data to be collected such as habitat attributes (e.g., richness, abundance.)
    b. Describe the data collecting methods and procedures, including guidelines for spatial coverage, temporal intervals, and data acquisition techniques. Include a plan or recommendations for integrating the use of remote sensing technology, e.g. how, when and where to acquire and use remote sensed imagery
    c. Establish quality control protocol
    d. Work with partnering agencies to identify funding opportunities

Qualified personnel	Biologist; Ecologist; Planner; Coastal Engineer			
Ranking	Fundamental principles	Chronology	Regional Applicability	Affordability
	(0)	(2)	(3)	(3)
Overall ranking	(8)			

Agenda 5.1 Conceptual Models and Monitoring Protocols Development

4. Identify and test metrics to quantify hazard mitigation performance, including storm surge reduction, wave attenuation, and shoreline erosion
    a. Review and update previously proposed metrics such as those from the USACE North Atlantic Coastal Comprehensive Study
    b. Improve existing metrics customized for NYC region and identify critical parameters impacting the applicability of hazard mitigation performance metrics
    c. Explain how to use the metrics, how to define/select control sites for testing the proposed NYC specific-metrics and benchmarking project performance
    d. Recommend a process for adding or removing parameters as the state of the science evolves
    e. Describe recommendations for monitoring programs development (Task 5.1.5)

Qualified personnel	Coastal Engineer; Hydraulic Engineer; Physical Oceanographer			
Ranking	Fundamental principles	Chronology	Regional Applicability	Affordability
	(0)	(3)	(3)	(3)
Overall ranking	(9)			

5. Develop monitoring protocol for collecting hydrodynamic and water quality data
    a. In coordination with Task 5.1.4, prioritize the data to be collected such as bathymetry, water levels, wave parameters, and water quality data (e.g., TSS, Chlorophyll-*a*, characteristic pollutants)
    b. Describe the methods and procedures for collecting various categories of data, including guidelines on spatial coverage (e.g., transects for water level and wave data collection), temporal intervals, and data acquisition techniques. Include a plan or recommendations for integrating the use of remote sensing technology, e.g. how, when and where to acquire and use remote sensed imagery
    c. Establish quality control protocol
    d. Work with partnering agencies to identify funding opportunities

Qualified personnel	Coastal engineer; Hydraulic engineer			
Ranking	Fundamental principles	Chronology	Regional Applicability	Affordability
	(0)	(2)	(3)	(3)
Overall ranking	(8)			

Agenda 5.2	Development of Rapid Assessment Tools and Ecosystem Models

Motivation

In order to evaluate the likely future conditions both with and without projects (e.g. cost/benefit type analysis for ecosystem valuation of CGI strategies), rapid assessment tools and/or more detailed ecological models can be used to compare the net benefits of projected habitats for various scenarios. The rapid assessment tools and ecosystem models will utilize metrics proposed in Task 5.1.2 to assess net ecosystem benefits across habitats developed by implementing different CGI projects. Proposed CGI projects can be prioritized according to the anticipated net ecosystem benefits relative to future without project conditions.

A rapid assessment tool can be developed to provide a means to measure or evaluate the structure, composition, and function of an ecosystem operating within a range of conditions (e.g., historic, current, predicted). The assessment would provide an index of ecological integrity based on metrics of biotic and abiotic condition, size, and landscape context. The assessment tool could be developed based on previously developed rapid functional assessments tailored for various habitats including:

- Benthic Index of Biotic Integrity (B-IBI) for sub-tidal habitats;
- Evaluation of Planned Wetlands (EPW) for coastal wetlands; and a
- Modified EPW Index for upland forest and shrubland communities.

Using the tool, an index (or score) can be obtained for the different habitats assessed, and be combined to quantify the value of a restoration project which may target multiple habitat types. Such a tool allows agencies to make consistent scientifically informed regulatory, planning, and other management decisions. The tool could potentially be based on the calculation of Functional Capacity Indexes (FCIs) and Units (FCUs) to provide a quantitative means to sum benefits of a restoration project across multiple habitats. An FCI is a measure of functional capacity expressed as an index, based on relationship between CGI strategy elements and the function. An FCI characterizes the integrity or condition of an ecological function or service with little or no consideration of a projects size. An FCU serves as a standardized basis for comparing functional differences over space and time. Therefore, an FCI represents the “quality” of functional capacity per unit area, whereas an FCU represents the “quantity” of functional capacity. FCUs could be calculated by multiplying the FCI by the area of the assessment area and be improved upon based on available data.

For more detailed assessments, spatially varying ecosystem models could be developed for the region. For instance, SLAMM and MEM are ecological models commonly used for simulation of wetland evolution. Additionally, EwE is a mass-balance assessment model, commonly used for fish species evaluation, which requires accurate baseline knowledge of reproduction, migration, mortality, and linkage with other species.

Agenda 5.2 Development of Rapid Assessment Tools and Ecosystem Models

Key questions

The following research questions have been identified. Section headings are annotated to indicate where questions are originated.

- What are the relevant ecosystem models currently available? What are the limitations of those models? (3.1)
- How to improve the basics of those models, e.g., increase spatial and temporal resolution, include more stressors? (3.1, 3.2)
- How to relate those models for NYC? (3.1, 3.2)
- How to rank net ecosystem benefits of an individual project across various CGI strategies? (2)
- How do the benefits of CGI approaches add/multiply/scale regionally? Is the whole greater than the sum of the parts? (2, 3.1)
- How to select a suite of projects for shoreline ecosystem restoration? (3.1)
- What are critical aquatic fauna species? (3.2)
- How do the aquatic fauna species respond to environmental variables, such as salinity, turbidity, and chemicals? (3.2)

Research tasks

1. This task works to coordinate relevant agency agendas regarding priority habitats and species. Many pilot projects and restoration attempts hinge on prioritizing particular species over others, emphasizing that critical habitat and wildlife are important not to disturb. However, many agencies have different lists or rankings of habitats, making pilot projects difficult to implement.
    a. Identify critical species and habitats relevant to overall agency goals
    b. Standardize and prioritize screening criteria
    c. Apply NYC-specific research to modify or add to this list of critical species
    d. Create an overall, agency-coordinated ranking of priority habitats and sites that will allow for more efficient permitting and design along the shoreline

Qualified personnel	Biologist; Ecologist			
Ranking	Fundamental principles	Chronology	Regional Applicability	Affordability
	(1)	(3)	(3)	(3)
Overall ranking	(10)			

Agenda 5.2 Development of Rapid Assessment Tools and Ecosystem Models

2. This task includes review and improvement of ecosystem models used to predict habitats and landscape morphology changes in NYC. These models will include consideration of climate change and be applied to approximate future conditions with and without project implementation in order to determine ecological benefits associated with each project.
   a. Review existing habitat/landscape evolution models (e.g., MEM, SLAMM)
   b. Identify models that are applicable for NYC habitats and model development needs to improve applicability locally
   c. As a proof of concept, apply models to evaluate habitat evolution for a range of proposed projects, including consideration of a representative future scenario

Qualified personnel	Biologist; Ecologist			
Ranking	Fundamental principles	Chronology	Regional Applicability	Affordability
	(1)	(1)	(3)	(2)
Overall ranking	(7)			

3. This task includes review and improvement of eco-path models used to predict fish biomass changes in NYC. Exploration of the basis of reproduction, interaction, and trophic linkage for a given fish species in biomass pools provides the fundamental knowledge base for predicting static or dynamic mass-balanced snapshots of the ecosystem. Data requirements can be obtained from stock assessment, ecological studies, or literature including biomass estimates, total mortality estimates, consumption estimates, diet compositions, and fishery catches. In addition, all the ecological aspects are subject to environmental changes, such as variations in salinity and turbidity that may affect the eco-path. To account for changes in environmental conditions due to sea-level rise or man-made structures, the mass-balance assessment of the system for the critical species can be used to evaluate the impacts of project placement and explore management policy options.
   a. Collect existing ecological data and establish an eco-path model for identified species in NYC
   b. Explore the effects of environmental variables, such as salinity, flow speed, turbidity on eco-path

Agenda 5.2 Development of Rapid Assessment Tools and Ecosystem Models				
c. As a proof of concept, apply eco-path models to evaluate biomass changes of key species (e.g., species identified in Task 5.2.1) for a range of proposed projects, including consideration of a representative future scenario				
Qualified personnel	Biologist; Ecologist			
Ranking	Fundamental principles	Chronology	Regional Applicability	Affordability
	(1)	(1)	(3)	(2)
Overall ranking	(7)			

4. This task includes review and improvement of rapid assessment tools applicable in NYC. These models will include consideration of climate change and be applied to approximate future conditions with and without project implementation in order to determine ecological benefits associated with each project. Quantification of the ecological benefits will utilize metrics defined in Task 5.1.2 and projected habitats using models in Task 5.2.2 and Task 5.2.3.
   a. Review existing rapid assessment tools for each pertinent habitat, e.g., tools being developed through Sustainable Shoreline project and HEP project
   b. Identify limitations that need be improved for NYC habitats
   c. Develop a scorecard system like FCI and FCUs to rank ecosystem benefits for each project
   d. As a proof of concept, apply the tools to evaluate habitat benefits for a range of proposed projects, including consideration of a representative future scenario

Qualified personnel	Biologist; Ecologist			
Ranking	Fundamental principles	Chronology	Regional Applicability	Affordability
	(1)	(3)	(3)	(3)
Overall ranking	(10)			

Agenda 5.3 Sediment study
Motivation

Understanding both the sediment budget and sediment longshore/cross-shore transport can provide important insight into the nature of the sedimentary system, landscape morphology, and the feasibility of particular CGI strategies. Analysis of the sediment budget (local or regional) requires adequate spatial and temporal observations of sedimentary processes, such as deposition rate, resuspension rate, and transport rate, as well as surficial sediment properties, such as grain size, sediment type, and soil strength. Existing datasets of sediment sampling are sparse and should be improved through high-resolution benthic sampling and computer modeling simulations. While sediment surficial sampling and sediment concentration measuring are expensive, computer modeling of sediment transport is more affordable and can be a powerful tool that integrates field measurements with scientific understanding, enabling more accurate interpretation of discrete observational data at a finer scale.

As a dense and urban environment, NYC itself also affects the sediment budget and sediment contamination in the harbor. For instance, Combined Sewer Overflows (CSOs) can alter both the direction and the source of sediments in the harbor. CSOs are recognized as the primary contaminant sources ubiquitous to the sediments of industrialized waterways. However, few studies can be found for the New York Harbor areas that investigate the effects of CSOs on sediment accumulation and quality.

A regional scale sediment transport model was developed to examine sediment contamination in the harbor area (Miller et al. 2011). Additionally, two ongoing projects funded through the Hudson River Foundation (HRF) focus on sediment transport, trapping and storage during extreme flow events (e.g., storms) in the Hudson River through numerical modeling and geological survey. The deliverables of these projects will improve the understanding of sediment movement and fate during high-energy event and provide more information about sediment resources in the Hudson. A continuation of these studies should explore the on-shore and longshore sediment dynamics during both normal and storm weather conditions, which can facilitate an understanding of suspended sediment load and bed-load.

With improved understanding of sediment dynamics, the existing regional sediment management plan (NY/NJ HEP 2008) can be improved and adapted for the NYC region for managing and searching quality sediment sources for coastal restoration projects. In conclusion, a sediment study will greatly benefit the planning and assessment of proposed CGI projects.

Agenda 5.3 Sediment study

Key questions

The following research questions have been identified. Section headings are annotated to indicate where questions are originated.

- What data are needed to estimate a sediment budget for the NYC area? (3.1, 3.3, 3.4, 4.1)
- What are the surrogates that people are using in the absence of a sediment study? (4.1)
- How do sediments migrate throughout the area? (4.1)
- How can numerical models improve the understanding of regional sediment dynamics? (4.1)
- How do CSOs affect sediment load/budget and quality? (3.1)
- Where are suitable sediment borrow areas? How much sediment is available? What is the cost? (3.1, 3.3, 3.4)
- How does soil strength vary throughout the region and how is that affected by different species of vegetation? (4.1)
- Is there a known relationship between sediment properties and habitat values (e.g., oysters, clams, and wetlands)? (4.1)
- How can regional sediment resources be managed effectively? (4.1)

Research tasks

1. Estimate an NYC area sediment budget, including consideration of sediment inputs from CSOs and riverine systems
    a. Desktop data collection to locate available sediment surveys
    b. Review the existing sediment transport model (Miller et al. 2011) and develop a regional hydrodynamic, sediment transport model
    c. Apply the numerical model to identify the effects of spatial and temporally varying deposition and resuspension rates on the sediment budget; to examine the effects of storm events on sediment dynamics; to review the possibility of some strategies for trapping quality sand.
    d. Estimate regional and site-specific (e.g., Jamaica Bay) sediment budgets
    e. Conduct a detailed evaluation of the effects of CSOs on the regional and site specific sediment budgets

Qualified personnel	Coastal Engineer; Coastal Modeler; Hydraulic Engineer; Marine Geologist			
Ranking	Fundamental principles	Chronology	Regional Applicability	Affordability
	(0)	(3)	(2)	(3)
Overall ranking	(8)			

Agenda 5.3 Sediment study

2. Soil strength evaluation
    a. NYC Parks has 24 sampling sites in salt marshes to test soil strength. Additionally, TNC is coordinating a Marsh Elevation Network research project between the USFWS, USEPA, USGS, and NYCDPR to estimate the shear strength of soils in Long Island, Jamaica Bay, Pelham Bay, and Staten Island marshes. Review these data upon project completion and identify gaps where more data need to be collected
    b. Using the available data, explore the relationship between different species of vegetation and soil strength
    c. If necessary, measure the soil strength where data are scarce

Qualified personnel	Geologist; Ecologist			
Ranking	Fundamental principles	Chronology	Regional Applicability	Affordability
	(0)	(3)	(1)	(2)
Overall ranking	(6)			

3. Identification of sediment borrow sources and development of a regional sediment management plan
    a. Identify possible sediment borrow sites
    b. Estimate sediment availability and quality (grain size, organic matter, contaminants, etc.)
    c. Examine the cost of dredging and transport
    d. Evaluate environmental and ecological impacts of excavation of sediment at given sites
    e. Improve the existing regional sediment management plan, adapt it for NYC
    f. Perform physical model testing to study sediment patterns near project area

Qualified personnel	Coastal Engineer; Ecologist; Environmental Engineer			
Ranking	Fundamental principles	Chronology	Regional Applicability	Affordability
	(0)	(3)	(2)	(2)
Overall ranking	(7)			

Agenda 5.4 Ice Study

Motivation

One of the factors which differentiate shorelines in the northeast from those in other areas of the country where CGI projects have been implemented is the presence of ice. Ice represents a significant destabilizing force and can be a primary factor in the erosion of exposed natural sites. Shore protection projects, whether traditional or non-traditional, are subject to damage from both static and dynamic ice loading. Moving ice can damage coastal structures by exerting significant impact forces when large pieces of ice transported by the prevailing currents collide with existing structures. Static ice forces resulting from ice formation on and adjacent to the elements of coastal protection projects, can be equally damaging. Plants utilized in CGI projects are particularly vulnerable to erosion during the first few growing seasons when the root systems are still developing.

In spite of its importance, our current understanding of the prevalence, typology, and extent of ice cover in the northeast is severely limited. Several limited studies of ice characteristics have been conducted but the data are sparse. Furthermore, our ability to incorporate ice into existing hydrodynamic models is limited due to the difficulty in modeling ice formation and growth. This lack of ice data (real or modeled) contributes to the lack of guidance for incorporating ice forces into the design of both traditional and CGI coastal protection works.

Key questions

The following research questions have been identified. Section headings are annotated to indicate where questions are originated.

- How to quantify the static and dynamic ice forces being exerted on coastal structures? (3.2)
- How to quantify the static and dynamic ice forces being exerted on natural shorelines? (3.1, 3.5, 3.6)
- How prevalent is ice along the shorelines of NYC, and what are its characteristics? (4.1)
- How does ice impact the living elements of CGI projects (both vegetation and animal life)? (3.6)
- How guidelines are best improved for the design of coastal structures in icy environments? (3.5, 3.6)
- Which plant communities are most vulnerable to uprooting related to ice? (3.1)

Agenda 5.4 Ice Study

Research tasks

1. Quantify and map ice volumes (typical and ranges) in NYC using remote and in-situ testing techniques.

Qualified personnel	Engineer; Geographer			
Ranking	Fundamental principles	Chronology	Regional Applicability	Affordability
	(0)	(3)	(2)	(3)
Overall ranking	(8)			

2. Assess the dynamic and static ice forces on both natural and built coastal infrastructure through field and laboratory studies.

Qualified personnel	Coastal Engineer			
Ranking	Fundamental principles	Chronology	Regional Applicability	Affordability
	(1)	(2)	(2)	(2)
Overall ranking	(7)			

3. Explore the risk of freezing damage on structures and vegetation types and identify metrics to monitor structures and shoreline stability

Qualified personnel	Coastal Engineer; Ecologist			
Ranking	Fundamental principles	Chronology	Regional Applicability	Affordability
	(1)	(2)	(2)	(2)
Overall ranking	(7)			

Agenda 5.4 Ice Study				
4. Improve the capability to model ice in existing hydrodynamic models in order to: a. Establish a model based ice climatology b. Increase the potential resolution of ice data sets c. Improve navigation d. Improve environmental management				
Qualified personnel	Coastal Engineer			
Ranking	Fundamental principles	Chronology	Regional Applicability	Affordability
	(1)	(2)	(2)	(2)
Overall ranking	(7)			

Agenda 5.5 Vessel Wake Assessment

Motivation

Wakes represent a potentially significant destabilizing force that is typically neglected in the design of coastal protection strategies. Traditionally, coastal structures are designed to resist wind-generated waves; however, recent studies have shown that wakes can be as large or larger in many parts of the Hudson. Ferries, tugs, and barges generate large and frequent wakes along the main stem of the river, while high-speed recreational vessels used for wake boarding, water skiing, parasailing, speed boating, and jet-skiing can generate large wakes even in relatively sheltered stretches of the river. The importance of understanding the influence of wakes in the Hudson is important because wave height drives the design of most coastal protection projects. For CGI projects, accurately establishing the wave climate including the wakes is critically important because the projects typically involve vegetation and smaller structural elements. Unlike traditional structures, such as bulkheads and revetments where over-design is common, the desire to work in smaller, more natural elements requires more careful consideration of boat wakes.

Key questions

The following research questions have been identified. Section headings are annotated to indicate where questions are originated.

- How do wakes impact the design of CGI projects and temporary stabilization of vegetation?
- How can knowledge regarding wave climate, including vessel wakes which are often more important than wind waves, be improved to aid in the design and planning of CGI projects, e.g., constructed reefs, ecological enhanced bulkheads, and living shorelines? (3.2, 3.5, 3.6)
- How do vessel wakes change project long term maintenance needs and failure rates?
- Are the existing vessel wake formulas accurate enough for use in NYC? (3.2, 3.5, 3.6)
- How much do the wakes change between their point of generation and the shoreline in different portions of the Hudson? (3.2, 3.5, 3.6)
- What are the vessel activity levels in riverine and sheltered bay areas (daily, weekly, monthly, seasonally variation)? (3.6)
- Can numerical models be used to predict/hindcast wake energy at the shoreline? (3.6)
- How can numerical models help develop a wave atlas to map wave heights due to vessel wakes under various vessel activity levels (in different months/seasons)? (3.6)

Agenda 5.5 Vessel Wake Assessment				
Research tasks				
1. Determine locations throughout NYC to deploy measurement devices and obtain wake wave height measurements. Data will be analyzed to improve and/or verify wake wave height formulas using NYC-specific field data.				
Qualified personnel	Coastal Engineer			
Ranking	Fundamental principles (0)	Chronology (1)	Regional Applicability (3)	Affordability (1)
Overall ranking	(5)			
2. Develop a numerical model to create a wake wave atlas considering various levels of vessel activity and vessel types a. Conduct a statistical analysis of vessel activity levels b. Develop numerical models capable of representing ship dynamics in the NYC area c. Create a wake wave atlas based on numerical model outputs				
Qualified personnel	Coastal Engineer; Coastal Modeler			
Ranking	Fundamental principles (0)	Chronology (3)	Regional Applicability (3)	Affordability (3)
Overall ranking	(9)			

Agenda 5.6 Cross-Agency Data and Metadata Management

Motivation

Project evaluations, of both hazard mitigation and ecological benefits, often require considerable observational data collection. Abundant data can improve the understanding of NYC baseline conditions and can provide a better framework in which CGI projects will be designed and implemented. However, data gaps were identified by a preliminary review, for instances, benthic habitat data, vessel wake heights, ice related data, etc. (further described in Table 5). In order to organize the large volume of data that currently exists and will be collected for various projects, a cross-agency data management tool is recommended. The tool could facilitate data sharing and dissemination, as well as reduce the long-term costs of data acquisition by avoiding redundant data collection efforts.

In addition to observational data, the systematic documentation of metadata for proposed and implemented projects in NYC can help regulators, designers, and researchers access the most recent/updated project information including goals and objectives, strategy types, innovative design concepts, implementation challenges, performance evaluations, lessons learned, etc. The European Union has leveraged a similar metadata database to improve consistency across projects and overall integrated coastal zone management.

Key questions

The following research questions have been identified. Section headings are annotated to indicate where questions are originated.

- How to develop the observation data management program? Which agencies and other stakeholders would be interested in participating? Who can be the host? How will the data be collected from the different agencies? (4.3, 4.4)
- How to develop a metadata dissemination platform? Is there an existing platform that could be adapted for NYC? (4.4)
- What are the funding sources to both start and sustain a program? (4.3, 4.4)

Agenda 5.6 Cross-Agency Data and Metadata Management

Research tasks

1. Develop a observational data management program and call for collaboration
   a. Work with agencies and other stakeholders interested in participating to create a platform that would provide maximum benefit to collaborators and other end users
   b. Identify data types to be hosted
   c. Determine data formatting protocols that will be most effective if they become fundamental to data collection for participating groups
   d. Identify existing data which could be migrated to the platform and reformat data to meet designated protocols
   e. Determine a host (of virtual server) and design a dissemination platform
   f. Identify potential funding sources

Qualified personnel	Computer Scientist; Planner; Coastal Engineer; Ecologist			
Ranking	Fundamental principles	Chronology	Regional Applicability	Affordability
	(0)	(1)	(2)	(3)
Overall ranking	(6)			

2. Develop a project library (metadata database)
   a. Locate metadata for implemented projects (only those being monitored) and proposed projects in NYC, e.g., project goal/objectives, strategic plan, critical project elements, monitoring plans
   b. Establish a platform to host project data, including the ability to make project inquiries using standard taxonomy

Qualified personnel	Computer Scientist; Planner; Coastal Engineer; Ecologist			
Ranking	Fundamental principles	Chronology	Regional Applicability	Affordability
	(0)	(3)	(3)	(3)
Overall ranking	(9)			

Agenda 5.7 Comparison of Marsh Species – Phragmites and Spartina

Motivation

Along the north Atlantic coast, the invasive reeds *Phragmites* have aggressively overtaken the native marshes, such as *Spartina*. *Phragmites* has been regarded as an aggressive invasive species that are often dismissed because its behavior of significant encroachment, such as shouldering aside *Spartina* and other native marsh grasses, growing tall and dense and rampant, choking waterways, and reducing biodiversity. It has been suggested that "*Phrag*mites is less populated by fauna", *Spartina* is "better", etc. However, recent studies have posted dissenting opinions that *Spartina* is not necessarily "better" and *Phragmites* has significant ecosystem values. Recent studies (especially in New Jersey) have shown that *Phragmites* is as good a habitat for some fauna species (e.g., ribbed mussel, crabs) as *Spartina*. One marsh species more populated by fauna or less populated should be a case-by-case judgment. More studies should be carried out to explore the eco-path of various species in the new habitat rife with *Phragmites*.

On the other hand, as the value of wetlands in protecting mainland communities is recognized, it is of great need to examine the capability of *Phragmites* to dissipate wave energy and to reduce water flow. *Phragmites* grows dense and tall (which favors wave energy dissipation) compared to *Spartina*. Differences in individual shoot, spatial distribution, and growth chart between these two species need to be further explored, however, in both field and laboratory experiments. Additionally, physical and numerical models can be developed to measure the Manning's friction coefficient (or drag coefficient) of *Phragmites, Spartina,* and other coastal wetland species under a variety of flow and wave environments.

Key questions

The following research questions have been identified. Section headings are annotated to indicate where questions are originated.

- What are the bio-mechanical properties of *Phragmites* and *Spartina* in NYC coastal habitats? (3.1)
- How resistant are *Phragmites* and *Spartina* to steady and oscillatory flows under a wide range of turbulent conditions? (3.1)
- What are the appropriate formulas to estimate vegetative resistance for a wide range of submergence degrees (from emergent to deeply submerged)? (3.1)
- How can a physical model be set up to help improve the understanding of friction coefficients for *Phragmites* and *Spartina*? (3.1)

Agenda 5.7 Comparison of Marsh Species – Phragmites and Spartina

- What are the ecological tradeoffs; *Phragmites* versus native marsh like *Spartina*, or no marsh? (3.1)
- How adaptable are *Phragmites* and *Spartina* to sea-level rise? (3.1)

Research tasks

1. Flow resistance evaluation of *Phragmites* and *Spartina*
   a. Collect bio-mechanical properties of *Phragmites* and *Spartina*
   b. Assess Manning's coefficient (or drag coefficient) in a laboratory flume using natural plants as bed lining
   c. Using laboratory experiment results, improve and calibrate vegetative resistance formula related to flexible plants
   d. Create or improve a numerical model that includes a coupling between vegetation resistance, flow conditions, and vegetation properties

Qualified personnel	Coastal engineer; Ecologist			
Ranking	Fundamental principles	Chronology	Regional Applicability	Affordability
	(1)	(2)	(3)	(2)
Overall ranking	(8)			

2. Evaluate species diversity, abundance, and population of birds and other wildlife in the presence of *Phragmites* and *Spartina*
   a. Conduct a detailed literature review for *Phragmites* and *Spartina*
   b. Collect observation data as necessary for locations in NYC
   c. Using metrics determined in Task 5.1, further evaluate and quantify the ecological benefits of *Phragmites* and *Spartina*

Qualified personnel	Ecologist			
Ranking	Fundamental principles	Chronology	Regional Applicability	Affordability
	(1)	(3)	(3)	(1)
Overall ranking	(8)			

Agenda 5.7 Comparison of Marsh Species – Phragmites and Spartina				
3. Revise and recommend *Phragmites* management practices. a. Investigate the impacts on water quality due to the use of herbicides or burning to clear *Phragmites* b. Investigate creative management practices which, instead of removal for restoration of native marshes, can consider shoreline stabilization, water filtration, nutrient sequestration, raw material provision, and/or forage provision for primary management purposes				
Qualified personnel	Environmental Engineer; Planner			
Ranking	Fundamental principles	Chronology	Regional Applicability	Affordability
	(0)	(1)	(1)	(3)
Overall ranking	(5)			

Agenda 5.8 Pilot Project Identification, Implementation, and Monitoring (Living Laboratory)

Motivation

Many hypotheses related to the hazard mitigation potential and ecological benefits of CGI strategies require field observation data to further evaluate and refine. Pilot projects are critically important to systematically address hypothesis that require field observations and monitoring. This is especially the case for non-traditional projects, which lack lessons learned and success stories from similar installations in NYC or elsewhere.

For each pilot project:

- Performance and affecting factors can be examined;
- Relationships between strategy types, shoreline location, and adjacent shoreline conditions can be evaluated;
- Proposed design and/or regulatory guidelines can be tested; and
- Performance metrics for given strategy types can be created and/or refined based on observational data.

Because pilot projects are often fundamental to furthering the science and may be challenging to implement due to regulatory and cost considerations, it is recommended that pilot studies in the area be prioritized prior to implementation.

Key questions

The following research questions have been identified. Section headings are annotated to indicate where questions are originated.

- What are the minimum pilot project scales? (2, 3.1, 3.2, 3.3, 4.1, 4.3)
- Which project attributes are critical to hazard mitigation and ecological benefits? (3, 4.1)
- How does the geographic location affect the performance of each CGI strategy (e.g., compare the performance of wetland projects in various locations throughout NYC)? (3.1)
- Which CGI strategies likely provide the most significant ecological benefits, hazard mitigation, or both at a given location? (2, 3)
- What strategies are likely to exhibit more substantial benefits when incorporated into a multi-strategy complex? (2, 3)

Agenda 5.8 Pilot Project Identification, Implementation, and Monitoring (Living Laboratory)

- Can the pilot project study resolve regulatory concerns for permitting non-traditional CGI projects? If yes, what are important data or indicators that should be introduced for improving the existing permitting process? (4.1, 4.2, 4.3)

Research tasks

1. Pilot project identification
   a. Identify hypotheses to be evaluated via pilot projects
   b. Conduct a literature review and stakeholder survey to identify potential pilot projects for each CGI strategy type
   c. Make recommendations for the implementation of proposed pilot projects and their associated monitoring programs to further align hypothesis and proposed projects
   d. Work with stakeholders to determine prioritization factors
   e. Establish a prioritization of pilot projects in the NYC area

Qualified personnel	Ecologist; Coastal Engineer; Planner			
Ranking	Fundamental principles	Chronology	Regional Applicability	Affordability
	(1)	(3)	(3)	(3)
Overall ranking	(10)			

2. Pilot project implementation and monitoring
   a. Work with partner agencies to implement consistent monitoring protocols (Task 5.1) across pilot projects
   b. Collect post-process and host monitoring data in an accessible platform (Task 5.6)
   c. Using the available monitoring data, test the hypotheses proposed for evaluation, e.g., oyster habitat in high-wave energy environments

Qualified personnel	Ecologist; Coastal Engineer; Planner			
Ranking	Fundamental principles	Chronology	Regional Applicability	Affordability
	(1)	(0)	(3)	(1)
Overall ranking	(5)			

Agenda 5.9 Evaluation of the Regulatory Process

Motivation

More frequent implementation of CGI in NYC and the State may ultimately require changes to regulatory processes that can streamline CGI permitting. Research by the Georgetown Climate Center (2013) showed that most standard USACE permitting favors a "hard" engineering approach to shorelines. However, in precedents from Alabama and Maryland, states have worked with the USACE to encourage living shorelines, through Programmatic General Permits and Regional General Permits, as well as offering to provide additional technical guidance on design, construction, and evaluation of CGI. Similarly, living shorelines in Virginia and Rhode Island are more widely applied than elsewhere, in part due to changes in governing legislation. While these specific permits may not be applicable in NYC and New York State, a similar process toward streamlining CGI permitting could be proposed to justify a framework for a potentially simpler and quicker decision. For example, where results of pilot studies could demonstrate that certain types of CGI projects provide improved ecosystem services, it may be possible to acquire a SAP, which is similar to the USACE Nationwide General Permit. Permitting CGI using a Standard Activity Permit (SAP) would have the added benefit of relieving some of the regulatory burden on limited personnel by simplifying the approval of CGI beforehand.

Another concern is that there is currently no agreement among agencies on conservation goals, priority species, and habitats (especially benthic habitat) for NYC, which makes decision making and permitting difficult. Achieving consensus on key habitat, species, and indicators requires more detailed benthic and habitat data and focused discussion.

Key questions

The following research questions have been identified. Section headings are annotated to indicate where questions are originated.

- What existing regulations inhibit the adoption of CGI? Can they be modified in a way that preserves their intent, but still allows for innovative engineering solutions which include CGI? (2)
- Are there opportunities in the existing regulatory framework to enable implementation of CGI? (2)
- What would be required to make CGI projects eligible for a SAP? (2)
- How should a habitat tradeoff analysis be structured to evaluate habitat values (e.g., mudflat versus converted salt marsh) in a way that is acceptable within the existing regulations? Should existing regulations be re-evaluated to consider habitat tradeoff differently? (2)

<table>
<tr><td colspan="5">Agenda 5.9 Evaluation of the Regulatory Process</td></tr>
<tr><td colspan="5">· Which benthic and habitat data are necessary to aid in decision making? How can that data be best collected and shared amongst agencies? (2)
· What are the minimum pilot project scales, minimum monitoring timelines, etc. to aid in the refinement of the regulatory framework? (2)
· How can consensus on key habitat, species, and indicators be achieved amongst regulators? (2)</td></tr>
<tr><td colspan="5">Research tasks</td></tr>
<tr><td colspan="5">1. Research the existing regulatory framework, SAP requirements, and coordinate regulatory agencies.
a. Conduct a literature review to identify opportunities in the existing regulatory framework to enable implementation of CGI and investigate the steps required to make CGI projects eligible for a SAP.
b. In cooperation with Tasks 5.1, 5.6, and 5.8, support the process to reach an agreement on the path forward for conceptual model development, data acquisition and management, and pilot studies through coordination between agencies.
c. Host workshops and/or meetings with regulators to build toward a consensus on possible regulatory reform.</td></tr>
<tr><td>Qualified personnel</td><td colspan="4">Planner; Permitting Specialist</td></tr>
<tr><td rowspan="2">Ranking</td><td>Fundamental principles</td><td>Chronology</td><td>Regional Applicability</td><td>Affordability</td></tr>
<tr><td>(0)</td><td>(0)</td><td>(3)</td><td>(2)</td></tr>
<tr><td>Overall ranking</td><td colspan="4">(5)</td></tr>
</table>

Agenda 5.10 Shoreline assessment for appropriateness of CGI Strategy

Motivation

As an initial screening tool for development and mitigation opportunities, it is necessary to understand what CGI and shoreline types exist currently, as well as which CGI strategies could be implemented along reaches of the existing shoreline. The study "Urban Waterfront Adaptive Strategies" conducted by NYC DCP developed a high-level overview of the shoreline typology and strategies description. However, a deeper dive of appropriateness of shorelines for different CGI strategies based on various considerations (e.g., CSOs, ice, waves, wakes, etc.) would be a helpful planning tool.

In coordination with Tasks 5.1, 5.2, 5.3, and 5.6, available data and metrics can be used to create a map that encodes each section of the NYC shoreline with the possible CGI techniques that are applicable and most beneficial, including consideration of sea level rise impacts on critical at-risk ecosystems (e.g., evaluate which ecosystems and locations may shift quickly or disappear with sea level rise). This type of map would allow for a more robust and data-backed decision making process and means to prioritize projects throughout the region.

Key questions

The following research questions have been identified. Section headings are annotated to indicate where questions are originated.

- Which CGI strategies are most applicable along the NYC shorelines for current conditions? (4)
- Which CGI strategies are most applicable along the NYC shorelines for future conditions? (4)
- Which shorelines present opportunities to provide the most substantial net ecological benefits using CGI strategies? (4)
- Which shorelines can be protected from event-based and gradual hazards using CGI strategies? (4)
- What are the screening criteria for prioritizing applicable CGI strategies? (4.1)

Agenda 5.10 Shoreline assessment for appropriateness of CGI Strategy				
Research tasks				
1. Develop a mapping tool displaying possibilities for CGI integration into the NYC shoreline a. Evaluate energy level of physical forces along each stretch of shoreline (in coordination with Task 5.1) b. Examine existing ecosystem and critical habitats c. Quantitatively or qualitatively assess net ecosystem benefits of potential CGI strategies d. Incorporate future sea-level projections into the mapping tool e. Use available data (Tasks 5.1, 5.3, and 5.6) to make a web based shoreline map that codes each section of shoreline with the applicable CGI strategies f. Enhance visualization capability, including a web portal so that agencies and designers can obtain background information (shoreline and CGI strategies) quick and easily				
Qualified personnel	Computer Scientist; Planner; Coastal Engineer; Ecologist			
Ranking	Fundamental principles	Chronology	Regional Applicability	Affordability
	(0)	(2)	(3)	(2)
Overall ranking	(7)			

Agenda 5.11 Coastal Resiliency Benefits Quantification of Wave and Current Velocity Reduction

Motivation

Traditionally the benefit of coastal protection strategies, such as levees and floodwalls, are based upon relationships between the depth of inundation and damages to structures and other infrastructure. For instance, USACE and FEMA benefit cost analysis (BCA) tools are founded on depth damage relationships.

However, CGI strategies generally have little to no impact on stillwater (storm tide) levels during storm events. Rather, the most significant hazard mitigation benefits from CGI strategies are reductions in current velocity and wave energy. Yet a systematic means to assess the economic impacts and damage reductions associated with these benefits has not been developed; traditional BCA tools are not able to capture the hazard mitigation and coastal resiliency benefits of CGI strategies.

CGI strategy hazard mitigation benefits are generally understood qualitatively. For instance FEMA Flood Insurance Rate Maps include V-Zone and Coastal A-Zone designations, which are areas with storm-induced waves. Often planning studies assess the impacts on V-Zone and Coastal A-Zone limits due to CGI strategy implementation as a means to demonstrate reduced wave action and flood hazards. However, the direct damage reduction benefits of decreased wave action and current speeds has not been quantified (e.g., monetized) in a generally accepted way such that the benefit of CGI strategies can be compared to one another and to traditional coastal protection measures.

Key questions

The following research questions have been identified. Section headings are annotated to indicate where questions are originated.

- What are the coastal resiliency and protection targets that should be identified (e.g., wave reduction, reduced structure count in the floodplain, reduced structure count in high wave zones, etc.) (4)
- Can existing BCA tools be updated to quantify coastal resiliency benefits such as reduced current speeds and wave energy?
- Which data are necessary to quantify coastal resiliency benefits? Which data are available?

Agenda 5.11 Coastal Resiliency Benefits Quantification of Wave and Current Velocity Reduction				
Research tasks				
1. Develop a methodology for quantifying coastal resiliency benefits a. Conduct a literature review of existing studies quantifying the benefits of reduced wave energy and current velocities b. Determine the necessary tools and data to develop a methodology that could be applied in the NYC area i. Infrastructure data (e.g., partial damage and failure mechanisms related to high currents and wave energy) ii. Data to monetize the damages associated with infrastructure iii. Representative without project wave and current velocities iv. In association with Section 6 agenda items, identify numerical models to determine with project wave energy and current velocity reductions c. Recommended methodology(s) for quantifying hazard mitigation benefits of CGI strategies and other coastal and riverine infrastructure designed to reduce current velocities and/or wave energy				
Qualified personnel	Coastal Engineer; Structural Engineer; Civil Engineer; Economist			
Ranking	Fundamental principles	Chronology	Regional Applicability	Affordability
	(1)	(2)	(3)	(2)
Overall ranking	(8)			

6. Strategic Research Plan

6.1. Constructed Wetland Research Agendas

Agenda 6.1.1	Vegetative Flow Resistance and Storm Wave Attenuation Potential of Salt Marsh and Maritime Forest
Motivation	
A key element of a constructed wetland (i.e., salt marshes) and maritime forests is vegetation. In comparison to the bottom friction of a bare seabed, vegetation in constructed wetlands and living shorelines provides significant resistance to water flows, dissipating momentum and energy. There are empirical and theoretical formulas available for estimating vegetative resistance; however, the formulas and coefficients, e.g., Manning's coefficient and drag coefficient, are typically developed from a given set of field or laboratory conditions, which range from bio-physical properties of a single plant and plant community to physical flow conditions. Another concern is that salt marshes and maritime forests are often fragmented by natural or human disturbances. Understanding the effects of patch dynamics can help avoid the overestimation of protective value of these vegetated systems, while improving the design to promote a more effective arrangement. This study further 1) tests existing vegetative resistance formula and friction coefficients; 2) examines the potential of intact and fragmented (patchy) wetland and maritime forests for reducing storm surge and waves; and 3) explores surge/wave reduction capability and its relationship with internal and external factors.	
Key questions	
The following research questions have been identified. · What are the bio-mechanical properties of coastal wetlands and coastal and maritime forests in NYC coastal habitats? · How resistant are coastal wetlands and maritime forests to marine forces under a wide range of turbulent conditions? · What are the appropriate formulas to estimate vegetative resistance for a wide range of submergence degrees (from emergent to deeply submerged)? · How can field measurements and physical model setup improve the understanding of	

Agenda 6.1.1 Vegetative Flow Resistance and Storm Wave Attenuation Potential of Salt Marsh and Maritime Forest

vegetative resistance (Manning's coefficient) of prevalent species of coastal wetlands and maritime forests in the NYC region? At what scale (horizontal and vertical) are constructed wetland and maritime forests effective at dissipating wakes and waves and reducing surge?

- How can numerical models be improved to more accurately predict the reduction in storm surge, wind waves and erosion due to vegetative resistance?
- How can patch complexity and dynamics (e.g, fragmentation, patch expansion and degradation) be parameterized in numerical models?
- How do patch dynamics affect the hazard mitigation potential?
- What are the minimum pilot project scales for providing targeted levels of protection and ecosystem services?

Research tasks

1. Flow resistance evaluation of coastal wetlands and coastal and maritime forests (in coordination with Task 5.7.1)
   a. For vegetative species other than *Phragmites* and *Spartina,* collect the necessary bio-mechanical properties
   b. Assess Manning's coefficient (or drag coefficient) in a laboratory flume using natural plants as bed lining
   c. Using laboratory experiment results or field transect data, improve and calibrate vegetative resistance formula applicable to both flexible and rigid plants

Qualified personnel	Coastal Modeler; Ecologist; Coastal Engineer			
Ranking	Fundamental principles	Chronology	Regional Applicability	Affordability
	(1)	(3)	(1)	(3)
Overall ranking	(8)			

2. Conduct a numerical study
   1. Improve the understanding of interactions between vegetation resistance, flow conditions, and vegetation bio-mechanical properties
   2. Examine the effects of patch dynamics (fragmentation, arrangement) on the

Agenda 6.1.1	Vegetative Flow Resistance and Storm Wave Attenuation Potential of Salt Marsh and Maritime Forest			
	protection value of salt marshes and maritime forests in the NYC area			
Qualified personnel	Coastal modeler; Ecologist			
Ranking	Fundamental principles	Chronology	Regional Applicability	Affordability
	(1)	(1)	(2)	(3)
Overall ranking	(7)			

3. Use numerical models to assess wave and surge reduction rates for internal (e.g., vegetative properties) and external (e.g., environmental conditions such as wave climates) variables such as project location, platform elevation, size, wetland continuity, proximity to other natural areas, and wave/surge dynamics. Studies should be organized in a systematic manner to test the sensitivity of wave and surge reduction for individual variables and the interaction between variables.

Qualified personnel	Coastal Modelers; Ecologist			
Ranking	Fundamental principles	Chronology	Regional Applicability	Affordability
	(1)	(0)	(2)	(3)
Overall ranking	(6)			

Agenda 6.1.2	Resiliency of Maritime Forests and Coastal Wetlands under a Natural, Healthy Condition and Impacts of Urban Nature

Motivation

NYC's salt marshes and maritime forests have proven especially vulnerable and are increasingly in decline. For example, wetland loss around Jamaica Bay has been reported at an annual rate of 1 to 2 percent. Fragmented salt marshes tend to be less resistant than healthy, intact marsh. Stability of coastal wetlands is not only related to the organic matter accumulation inherently but also to mineral sediment deposition. Maritime forests are subject to anthropological disturbance and natural disturbances, such as invasive species overtaking, salt spray, wind, and waves, under both normal and extreme weather conditions and climate change. Invasive species (plants or insects) could dramatically degrade the health of maritime forests making them less resistant to change (i.e., storm events, droughts). Resiliency is not merely an output of construction but one of ongoing conservation/natural resource management on many fronts of ecological integrity for target (ecological) communities or ecosystem services/benefits.

With sufficient sediment and nutrient load, constructed wetlands and maritime forests are sustainable strategies that can self-adapt to gradual hazards, such as sea-level rise, and can self-recover from moderate damage due to storm events. Although trends and concepts are generally understood, further studies are required to improve the broader communities' understanding of the resiliency of constructed wetlands and maritime forests, such that restoration efforts can be optimized.

Key questions

The following research questions have been identified.

- Can existing resiliency evaluation tools, e.g., the CRT developed by TNC, be improved to examine resiliency considering present and future flood and sea-level rise hazards for NYC?
- How to quantify (index) the resiliency of vegetation system?
- How is the resiliency affected by the urban settings of NYC?

Agenda 6.1.2	Resiliency of Maritime Forests and Coastal Wetlands under a Natural, Healthy Condition and Impacts of Urban Nature

Research tasks

1. Quantitatively assess resiliency of maritime forests and salt marshes (e.g., establish indices) including but not limited to:
    a. Identify factors contributing to marsh and maritime forest loss that threaten restored wetlands and their associated ecosystem benefits
    b. Review existing methods or models, e.g., CRT estimating coast resiliency to identify needs of improvement for NYC
    c. Examine self-recover time scale after a storm event and affecting factors and adaptability to sea-level rise.

Qualified personnel	Ecologist			
Ranking	Fundamental principles	Chronology	Regional Applicability	Affordability
	(0)	(2)	(2)	(3)
Overall ranking	(7)			

2. Quantitatively assess the impact of the highly urban settings of NYC on resiliency, including but not limited to:
    a. Fragmentation due to roads
    b. Nutrient load
    c. CSOs and other pollution effects

Qualified personnel	Ecologist; Coastal Hydrologist			
Ranking	Fundamental principles	Chronology	Regional Applicability	Affordability
	(1)	(1)	(2)	(3)
Overall ranking	(7)			

6.2. Reef Research Agendas

Agenda 6.2.1 Complex Flow and Wave Transmission Analysis of Constructed Reefs
Motivation
Recently, innovative designs of substrate units are more commonly implemented to build artificial reef substrate, replacing traditional rocks or rubble. The lightweight and hollow design makes construction easier and attracts more marine lives. Meanwhile, it is anticipated that that these units are able to reduce wave energy effectively and provide the potential to trap sediments. However, observational data and supporting numerical modeling analyses to quantify the impacts and optimize designs and feature benefits (e.g., wave transmission coefficient) are limited. Advanced hydrodynamic studies of these complex features require high-performance computations to simulate three-dimensional flows around and through the reef units to establish bulk flow parameters and surface wave transmission coefficients. These bulk flow parameters and surface wave transmission coefficients are to be developed such that they can be applied as part of further engineering analyses for design and performance comparison. An example would be bulk parameters informing a two-dimensional numerical modeling analysis to investigate the impacts of artificial reefs on regional circulation and wave dissipation.
Key questions
The following research questions have been identified. · What are the flow patterns through reef units? How are the flows affected by the shape and the void space of the unit? · What are the wave transmission coefficients of various artificial reefs? · How do project properties such as footprint shape, proximity to coast, and crest elevation affect wave transmission over reefs? · How does the surface roughness of reefs affect wave transmission? · What is the optimal crest elevation, considering structure stability and resiliency? · What is the circulation pattern behind the structure? How is that related to the residence time of the tranquil water? · How is sedimentation behind the reef impacted? · How are shellfish and finfish populations affected by flow speed and circulation patterns? · What is the optimal size for a constructed reef pilot study in order to quantify both ecological and coastal protection impacts?

Agenda 6.2.1	Complex Flow and Wave Transmission Analysis of Constructed Reefs			
Research tasks				
1. Quantify three-dimensional flow through complex reef units and improve the parameterization of bulk flow and wave dissipation. a. Develop an advanced three-dimensional model for the evaluation of flows in and around individual and multiple reef units b. Establish bulk flow parameters to be used in a project scale analysis c. Estimate the wave transmission coefficients d. Perform physical model testing to further evaluate flow and turbulence patterns				
Qualified personnel	Coastal Engineers; Coastal Modelers			
Ranking	Fundamental principles	Chronology	Regional Applicability	Affordability
	(1)	(3)	(1)	(3)
Overall ranking	(8)			
2. Conduct a proof of concept study to optimize project properties such as footprints, proximity to coast, and crest elevation to maximize wave attenuation and improve conditions for shellfish and finfish habitat. a. Develop a two-dimensional model for the evaluation of flows in and around individual and multiple reef units, which includes consideration of bulk flow parameters defined in Task 6.2.2 b. For an individual project site, optimize wave attenuation and flow parameters necessary for shellfish and finfish habitats to establish a general guideline for similar assessments c. In coordination with Task 5.1.4, test metrics for evaluation and optimization				
Qualified personnel	Coastal Engineers; Coastal Modelers; Marine Biologist			
Ranking	Fundamental principles	Chronology	Regional Applicability	Affordability
	(1)	(1)	(3)	(1)
Overall ranking	(6)			

Agenda 6.2.2 Oyster Habitat Assessment

Motivation

Constructed living reefs are desirable from an ecological viewpoint, although they are strictly limited by many environmental factors. Oyster reef pilot sites for example, have been limited to low to medium energy environments and tidal range must be strongly considered in any design. Additionally, oysters are highly susceptible to damage from debris, ice, and sometimes longshore shifting sediment, which as it builds up can suffocate the reef. From the 17th to 19th centuries, oysters occupied more than 350 square miles of the Hudson-Raritan Estuary from as far south as Sandy Hook to as far north as Ossining, New York (NY/NJ Baykeeper 2006). Oysters are now functionally extinct, with a loss greater than 99 percent in the Hudson-Raritan Estuary (NY/NJ HEP 2012). In a geological time scale, oyster colonizations succeed and diminish in the Hudson-Raritan Estuary due to warm-cool cycles.

Oyster reef systems require specific conditions in order for the species to thrive and become self-sustaining. Key considerations related to oyster habitat are:

- When placing reefs in NYC, water quality is one of the most important factors limiting colonization. Salinity, dissolved oxygen, and turbidity must all be within the optimal range for successful reef development. Additionally, pollutants, through CSOs altering the water's nutrient load, affect reef health.
- A freshet can have a large impact on the salinity of the lower portion of an estuary with a large river discharge like the Hudson, dramatically affecting key ecosystem processes (Rella 2014) and triggering oyster disease, MSX (Buzan et al. 2009).
- Predation by blue crabs and oyster drill may also cause serious damage to reefs.
- Historically, a combination of overfishing, pollution, and habitat destruction has led to the loss of oyster habitat.

There is a need to implement pilot projects and monitor the established oyster habitat, focusing on growth, survival, disease, and, most importantly, natural recruitment. Water quality monitoring should also take place and include pollution levels (metal or toxic chemical), salinity variation, water temperature, turbidity, and dissolved oxygen. Oyster reefs generally lack adaptive management plans after their deployment.

Key questions

The following research questions have been identified.

- What is the optimal survey interval? How long should various parameters be monitored?
- Can USACE monitoring criteria and recommendations be applied "as is" or improved for the

Agenda 6.2.2	Oyster Habitat Assessment

NYC coast?

- What are the impacts of MSX and oyster drill in NYC reefs? Is there a time period, relative to reef construction, in which oysters are most vulnerable to MSX and oyster drill?
- Which are the critical factors (water quality, substrate chemical, social) NYC destroying oyster reefs?
- How does the project scale affect oyster implantation and colonization? What are the properties of oyster substrate that determine oyster growth and multiplication and how?
- How is oyster colonization affected by flow speed and circulation patterns? How can larval transport be assessed at a harbor scale?
- What are properties of oyster substrate that determine oyster growth and multiplication and how?
- What are possible structural benefits achieved by developing oyster reefs on marine infrastructure (i.e., effect on structural strength, chloride penetration, physical forces absorption)?

Research tasks

1. Examine monitoring criteria, critical impact factors, and adaptive management of reefs
    a. In coordination with Task 5.1 and considering USACE monitoring criteria and recommendations, develop monitoring protocols for oyster reefs
    b. Evaluate the impacts of MSX, oyster drill, pollutants, and other critical parameters on oyster habitat in NYC
    c. Create a harbor-wide assessment model for larval transport in coordination with Task 5.3.1 (sediment transport model)
    d. Develop adaptive management criteria for oyster reefs in NYC

Qualified personnel	Ecologist; Biologist; Coastal Engineer			
Ranking	Fundamental principles	Chronology	Regional Applicability	Affordability
	(1)	(1)	(3)	(2)
Overall ranking	(7)			

6.3. Channel Shallowing Research Agendas

Agenda 6.3.1 General Research on of the Effects and Feasibility of Channel Shallowing for Flood Risk Reduction in NYC

Motivation

The channel shallowing strategy has the capability to reduce flooding substantially in locations like Jamaica Bay and potentially many other locations, as discussed and suggested in Section 3.4, the literature review for channel shallowing strategy. However, it is a new concept and there are many research questions to address if it is to be considered an applicable measure. Several fundamental research questions need to be addressed to help evaluate where this strategy could be helpful and how helpful it can be in reducing flood risk.

Research should begin with broad studies of the effects on flooding and waves for a range of location characteristics, including channel width, depth, and length, as well as inlets versus estuary channels. The study should utilize a range of storm types, from more common annual storm events to severe nor'easters and to hurricanes. The pairing of the channel shallowing strategy with wetland restoration has appeared to be synergistic because deep channels allow floodwaters to circumvent wetland areas; therefore, the cumulative benefits of these two strategies needs to be examined.

Channel shallowing, in most cases, is a difficult measure to utilize on a short time scale because deep channels are typically used for commerce or recreational activities or both. The concept in some cases can only be envisioned as a long-term solution, potentially even a passive approach where natural sedimentation fills the channel over many decades. As such, any study of the approach should include deeper research on flood resilience, where channel shallowing (potentially paired with wetlands) is compared to gray and green-gray solutions. These studies should address both how well the adaptations work when the flood elevation is within their design height, but also when the flood elevation exceeds design height. These studies should also closely evaluate the impact of each adaptation strategy over a century or longer time scale, in terms of flood risk reduction, given accelerating sea-level rise.

Key questions

The following research questions have been identified.

- What is the feasibility of shallowing a given channel, balanced against the utility of a channel for deep-draft vessels, in terms of all present uses of that channel, economic or municipal?
- What is the flood reduction benefit for this strategy for a variety of different flood events, from more common, annual floods to extreme cases like Hurricane Sandy or worse?

Agenda 6.3.1	General Research on of the Effects and Feasibility of Channel Shallowing for Flood Risk Reduction in NYC
Research tasks	

1. Search and identify potential channels that can be filled either by placing sediment fill or decommission of navigation usage; develop analytical (mathematical) or simplistic numerical model experiments to evaluate flood impacts of channel shallowing for a range of scenarios; or develop or use existing realistic, detailed models of local waterways to examine the efficacy of channel shallowing for flood reduction at a range of sites.

Qualified personnel	Coastal Engineer; Hydrodynamic Modeler; Hydraulic Engineer; Physical Oceanographer			
Ranking	Fundamental principles	Chronology	Regional Applicability	Affordability
	(1)	(3)	(1)	(3)
Overall ranking	(8)			

2. Develop methods for valuing flood reductions, the economic value of channel use by deep-draft vessels, valuing long-term (100+ year) resilience and not simply short-term resilience reflected in the 100-year flood and projected sea-level rise over decades. Apply these for example cases from NYC.

Qualified personnel	Economist, Sustainability Scientist			
Ranking	Fundamental principles	Chronology	Regional Applicability	Affordability
	(1)	(3)	(1)	(3)
Overall ranking	(8)			

Agenda 6.3.2	Environmental Study of the Channel Shallowing Strategy at a Feasible Location Motivation

Motivation

To determine whether or not shallowing is feasible for a given location, the same questions identified in the prior section must be addressed, but in the narrower context of the local site. Additionally, candidate in-fill methods and resulting in-fill time periods must be evaluated. The strategy has not been applied anywhere yet, and the method for shallowing is a crucial question. At one extreme, the method of shallowing could simply be initiated by decommissioning a dredged channel and allowing natural sedimentation over a longer period of time. At the other extreme, shallowing could be accomplished through direct sediment in-fill, similar to beach replenishment. Options like oyster farming, or the sand engine strategy, might be evaluated for their impact on in-fill and the rate at which resulting shallowing would occur.

The range of boating and shipping and other uses of deep channels need to be evaluated and weighed for a site. The shallowing strategy is challenging to implement because deep channels were initially dredged for shipping purposes and often have a wide variety of users. However, if a channel is no longer used, or the use requires only a shallower depth (e.g., for sailboats, fishing charters), then some level of shallowing is possible and natural shallowing is even likely if dredging is halted because its expense is no longer justified. Assessing tradeoffs between economic values versus ecosystem values after channel decommissioning is a key for this strategy.

Key questions

The following research questions have been identified.

- What are the effects of this strategy on the local sediment budget?
- Does this strategy complement restoration in terms of reducing deep-water pathways for flooding?
- Does this strategy complement wetland resilience due to removing a deep-water sink for sediments?
- What are the effects of sediment budget on the stability of this strategy?
- What are the differences in water quality and residence time with and without channel shallowing?
- What is the potential of this strategy for storm surge and wave reduction?
- What is the human and ecological value of this strategy, and how does it compare to the human value of the channel for vessels that would no longer be able to use the channel?
- What is period of natural infill, based on present-day sediment transport?

Agenda 6.3.2	Environmental Study of the Channel Shallowing Strategy at a Feasible Location Motivation
Research tasks	

1. Development of numerical models for circulation and transport.
    a. Develop numerical model to quantify storm surge reductions, effects of channel shallowing on sediment transport, and effects of channel shallowing on water quality and residence time inside the semi-enclosed water body.

Qualified personnel	Coastal Engineer; Hydrodynamic Modeler; Hydraulic Engineer; Physical Oceanographer			
Ranking	Fundamental principles	Chronology	Regional Applicability	Affordability
	(1)	(3)	(1)	(3)
Overall ranking	(8)			

2. Quantify the integrity of the restored habitats at a specific location.
    a. BACI requires immediate action of field data collection, including environmental and ecological variables
    b. Tradeoff analysis (habitat tradeoffs, ecosystem conservation, and urban development tradeoffs)

Qualified personnel	Coastal Engineer; Ecologist; Biologist			
Ranking	Fundamental principles	Chronology	Regional Applicability	Affordability
	(0)	(1)	(1)	(3)
Overall ranking	(5)			

6.4. Ecologically-enhanced Bulkheads and Revetments Research Agendas

Agenda 6.4.1 Ecologically-enhanced Bulkheads and Revetments Design Guidelines

Motivation

Bulkheads and revetments are common in urban areas, marinas, and along rivers and coasts where space is limited. For these reasons, bulkheads and revetments have been a favored shoreline stabilization approach in and around the area of NYC. For all their benefits, bulkheads and revetments have been shown to have a number of negative impacts related to ecological productivity. Recently, a variety of enhancements have been proposed (and in some cases applied) that aim to minimize some of these negative impacts, while preserving the stabilization function of the structure. The proposed enhancements take a variety of forms ranging from simply incorporating vegetation into an existing structure (joint planted revetment) to completely changing the geometry and composition of the structure. When designed correctly, the enhancements can furnish important shoreline characteristics and improve habitat areas for fish, shellfish, birds, mammals, and other aquatic and terrestrial life.

While the concept of ecologically-enhanced bulkheads and revetments has gained momentum recently, a number of questions remain about the usefulness and cost-effectiveness of these enhancements. For example, when using vegetation, there is a trade-off between the ecological benefits and the potential for adverse impacts if the vegetation becomes overgrown. While initially the root systems increase the structure stability and reduce the washout of soil, overgrown roots can displace armor stone, thereby destabilizing the structure as a whole. Additional research needs to be performed to assess the effectiveness of the different types of enhancements being proposed. Ultimately, a set of design guidelines needs to be developed that highlights the delicate balance between ecology, engineering, and aesthetic in these innovative projects.

Key questions

The following research questions have been identified.

- What is the stone size and depth of cover layer that is necessary for avoiding root wedging?
- To what extent can vegetation stabilize the bank and structure?
- If vegetation becomes overgrown, does it have an adverse effect on the shoreline?
- How does drift ice impact the ecologically-enhanced structure (in coordination with Task 5.4)?
- How do wakes impact ecological enhancements (in coordination with Task 5.5)?

Agenda 6.4.1	Ecologically-enhanced Bulkheads and Revetments Design Guidelines			
· What are the ecological and water quality benefits of enhancements relative to traditional solutions? · How successful is the ecologically-enhanced structure in providing hazard mitigation compared to its traditional form?				
Research tasks				
1. Define and standardize design guidelines for ecological enhancement a. Establish guidelines to determine stone size and armoring depth for bank stabilization features with joint planting b. Quantify the bank stabilization achieved by joint planting, including consideration of destabilization related to overgrowth of vegetation c. Recommend maintenance guidelines for vegetation growth if necessary d. Assess drifting ice conditions to determine design guidelines which will improve the success (e.g., limit uprooting) of ecological enhancements e. Evaluation of wake waves in design guidance f. Perform physical model testing to study flow patterns surrounding different structure types and ecological enhancements				
Qualified personnel	Coastal Engineer; Hydraulic Engineer; Ecologist			
Ranking	Fundamental principles	Chronology	Regional Applicability	Affordability
	(1)	(3)	(3)	(2)
Overall ranking	(9)			

Agenda 6.4.2 Structural Benefits of Marine Growth on Marine Infrastructure
Motivation
Many ecological alterations to marine infrastructure exist that are intended to increase the level of biomass accumulation or growth of marine fauna and flora on the structure. Methods include but are not limited to; constructing structures from materials that offer a suitable substrate for marine growth, providing enclosed spaces or areas with reduced turbulence to serve as nursing grounds, and providing a texturized surface to increase complexity. It has been proven that an increase in biological productivity can be achieved by implementing the listed techniques. These artificial habitats provide food and nesting habitat as well as sequestrate carbon, recycle biological material, and boost benthic productivity; significantly improving water quality at the site. However, the effects of the habitat on the structure itself have not been well documented. It has been proposed that increased growth reduces maintenance requirements, absorbs the forces from waves and debris, as well as increases the expected lifespan of the structure.
Key questions
The following research questions have been identified. · What effects does the growth of invertebrates on marine infrastructure have on the structural integrity of the material? · What effects does the growth of invertebrates on marine infrastructure have on its expected lifespan? · How does the accumulation of biomass on marine infrastructure affect its maintenance requirements? · How does the accumulation of biomass on marine infrastructure affect the amount of chloride penetration?

Research tasks

1. Identify and quantify structural benefits achieved from habitat growth
    a. Determine which materials can be applied to marine infrastructure and provide a suitable substrate for marine growth
    b. Identify the species and quantity of marine fauna and flora achieved by implementing ecological enhancements
    c. Quantify any increase in structural strength achieved from habitat growth
    d. Quantify the reduction of forces achieved by the accumulated biomass
    e. Determine any reduction in chloride penetration due to the presence of marine habitat

Qualified personnel	Coastal Engineer; Ecologist, Biologist			
Ranking	Fundamental principles	Chronology	Regional Applicability	Affordability
	(1)	(3)	(3)	(2)
Overall ranking	(9)			

6.5. Living Shorelines Research Agendas

Agenda 6.5.1 Living Shoreline Design Guidelines
Motivation
A commonly constructed form of living shoreline is a marsh area that is protected by a low-lying stone sill. One of the primary purposes of this strategy is to mitigate shoreline erosion and degradation, which is often caused by gradual processes under typical weather conditions and can be accelerated by acute events under stormy weather conditions. As a complex, the sill and the developed marshland components of the living shoreline reduce wave energy. The sill serves to protect the marsh plantings during typical tidal events, while the marsh stabilizes the shoreline and provides a last line of defense during storm events. However, the quantity of wave reduction depends on the size of the sill, marsh width, marshland vegetation type, and the local wave climate. A sill allows for a significant amount of habitat to develop between itself and the shoreline. By decreasing the energy of the water shoreward of the structure, marine fauna and flora can become established, where the wave energy would normally be too intense for habitat to develop. Spaces between the armoring stones, as well as irregularity (non-linear) of the shoreline can promote species richness and abundance. This is due to the water exchange, decreased current velocities, and sheltered space, which is viable habitat for fish and other marine organisms of varying sizes. Properly designed sills with appropriate crest height and window spacing allows for circulation, preventing the water behind the sill from becoming stagnant. The USACE currently uses a sill cross-section developed by Hardaway. However, additional research is needed for defining standardized design guidelines that address window spacing, distance offshore and other design features more specifically.
Key questions
The following research questions have been identified. · What are the optimum sill dimensions (e.g., sill height, window dimensions, and spacing) for various estuarine/riverine conditions (e.g., channel shape, seasonal flow rates)? · How effective are different sill materials (rock, gabions, bulkhead, living reefs) at dissipating waves and holding the front edge?

Agenda 6.5.1 Living Shoreline Design Guidelines
· How do marsh characteristics (elevation, plant density, width) influence energy dissipation? · How can edges be shaped to best enhance species richness and abundance? · How do poor underlying soil conditions impact the long-term stability of living shoreline projects? · How will sea-level rise impact living shoreline projects? · How does ice impact the living elements of CGI projects (both vegetation and animal life)? · How guidelines are best improved for the design of coastal structures in icy environments? How do wake waves impact living shorelines design guidelines? · How successful is the living structure compared to traditional structural strategies? What are the ecological benefits of living shorelines? How do we integrate ecological benefits into project selection criteria? Which materials are most successful at providing ecological and water quality benefits? · How can present regulations be modified to allow for adaptive management of living shoreline projects?
Research tasks
1. Develop a protocol (in coordination with Task 5.1.3) for the monitoring and assessment of living shorelines. a. Determine changes in water quality b. Determine changes in species abundance c. Determine shoreline stability d. Determine changes in marsh extent and vegetation e. Determine sediment accretion or erosion within the marsh

Qualified personnel	Coastal Engineer; Ecologist; Landscape Architect			
Ranking	Fundamental principles	Chronology	Regional Applicability	Affordability
	(1)	(2)	(3)	(3)
Overall ranking	(9)			

Agenda 6.5.1	Living Shoreline Design Guidelines

2. Define and standardize design guidelines for living shorelines
    a. Determine the tolerance to ice volume and force on sills and vegetation
    b. Evaluation of wake waves in design guidance
    c. Provide guidance for the creation of shoreline curvature to enhance species richness and abundance
    d. Determine guidelines for sill elevation, window dimensions, and distance to the existing shoreline, which determines the volume of sediment fill and size of habitat creation

Qualified personnel	Hydraulic Engineer; Ecologist			
Ranking	Fundamental principles	Chronology	Regional Applicability	Affordability
	(1)	(3)	(3)	(3)
Overall ranking	(10)			

3. Evaluate the wave and current energy dissipation provided by a range of edge types (e.g., sill dimensions, window spacing, bank sinuosity, material type) using physical models and field studies. Supported by Tasks 5.7, 5.8, and 6.1.1.

Qualified personnel	Coastal Engineer			
Ranking	Fundamental principles	Chronology	Regional Applicability	Affordability
	(1)	(0)	(3)	(1)
Overall ranking	(5)			

7. Research Summary

Agenda	Task	Brief Description	Prioritization: Fundamental principles	Chronology	Regional Applicability	Affordability	Overall weight
5.1 Ecological Conceptual Model and Monitoring Protocol Development	5.1.1	Develop conceptual model	0	3	3	2	7
	5.1.2	Identify/test metrics and control sites for habitat evaluation	0	3	3	3	9
	5.1.3	Develop ecosystem data monitoring protocol (coordinating with 5.1.2)	0	2	3	3	8
	5.1.4	Identify/test metrics to quantify hazard mitigation performance	0	3	3	3	9
	5.1.5	Develop environment data monitoring protocol (coordinating with 5.1.4)	0	2	3	3	8
5.2 Development of Ecosystem Models and CGI Projects Prioritization	5.2.1	Prioritize habitats and species	1	3	3	3	10
	5.2.2	Review and development of rapid assessment tools comparing net benefits across habitats	1	3	3	3	10
	5.2.3	Review and development of ecosystem models for landscape changes	1	1	3	2	7
	5.2.4	Review and improve eco-path models used to predict fish biomass changes (coordinating with 5.2.1)	1	1	3	2	7

Agenda	Task	Brief Description	Prioritization: Fundamental principles	Chronology	Regional Applicability	Affordability	Overall weight
5.3 Sediment Study	5.3.1	Estimate an NYC area sediment budget	0	3	2	3	8
	5.3.2	Soil strength in NYC coast areas	0	3	1	2	6
	5.3.3	Identify sediment borrow sources and develop a regional sediment management plan	0	3	2	2	7
5.4 Ice Study	5.4.1	Ice volume mapping	0	3	2	3	8
	5.4.2	Assess the dynamic and static ice forces	1	2	2	2	7
	5.4.3	Explore the risk of freezing damage on structures and vegetation types	1	2	2	2	7
	5.4.4	Improve the capability to model ice in existing hydrodynamic models	1	2	2	2	7
5.5 Vessel Wake Assessment	5.5.1	Determine locations throughout NYC to deploy measurement devices and obtain wake wave height measurements (requires instrument deployment)	0	1	3	1	5
	5.5.2	Create a wake wave atlas	0	3	3	3	9

Agenda	Task	Brief Description	Prioritization: Fundamental principles	Chronology	Regional Applicability	Affordability	Overall weight
5.6 Cross-Agency Data and Metadata Management	5.6.1	Develop the observational data dissemination portal and data management plan coordinating conceptual models development (5.1) and data collection (5.8)	0	1	2	3	6
	5.6.2	Develop a project library including project metadata and taxonomy	0	3	3	3	9
5.7 Comparison of Marsh Species -*Phragmites* and *Spartina*	5.7.1	Flow resistance of *Phragmites* vs. *Spartina* (Manning's coefficient)	1	2	3	2	8
	5.7.2	Evaluate species diversity, abundance, and population of birds and other wildlife in the presence of Phragmites	1	3	3	1	8
	5.7.3	Revise and recommend *Phragmites* management practices (coordinating with 5.7.1 and 5.7.2)	0	1	1	3	5
5.8 Pilot Project Identification, Implementation and Monitoring (Living Laboratory)	5.8.1	Pilot project identification	1	3	3	3	10
	5.8.2	Pilot project implementation and monitoring (coordinating with 5.1 and 5.6; time-demanding)	1	0	3	1	5
5.9 Evaluation of the Regulatory Process	5.9.1	Research the existing regulatory framework, SAP requirements, and coordinate regulatory agencies	0	1	1	3	5

Agenda	Task	Brief Description	Prioritization				
			Fundamental principles	Chronology	Regional Applicability	Affordability	Overall weight
5.10 Shoreline assessment for appropriateness of CGI Strategy	5.10.1	Develop a mapping tool displaying possibilities for CGI integration into the NYC shoreline	0	2	3	2	7
5.11 Coastal Resiliency Benefits Quantification	5.11.1	Develop a methodology for quantifying coastal resiliency benefits	1	2	3	2	8
6.1 Constructed Wetland Research Agendas	6.1.1.1	Flow resistance evaluation of coastal wetlands and coastal and maritime (coordinating with 5.7.1)	1	3	1	3	8
	6.1.1.2	Numerical model improvement for interactions between vegetation resistance, flow conditions and vegetation properties (coordinating with 5.7.1 and 6.1.1.1)	1	1	2	3	7
	6.1.1.3	Numerical study of wave and surge reduction potential and how are they affected by vegetation properties and storm dynamics (coordinating with 5.7.1, 6.1.1.1, and 6.1.1.2)	1	0	2	3	6
	6.1.2.1	Quantitatively assess resiliency of maritime forests and salt marshes (coordinating with 5.1.2)	0	2	2	3	7
	6.1.2.2	Quantitatively assess the impacts of the highly urban settings of NYC on resiliency (coordinating with 5.1.2 and 6.1.2.1)	1	1	2	3	7

Agenda	Task	Brief Description	Prioritization: Fundamental principles	Chronology	Regional Applicability	Affordability	Overall weight
6.2 Reef Research Agendas	6.2.1.1	Quantify three-dimensional flow through complex reef units and improve the parameterization of bulk flow and wave dissipation	1	3	1	3	8
	6.2.1.2	Optimize project attributes to maximize hazard mitigation and favor fish/shellfish abundance (coordinating with 5.1.4, and 6.2.2)	1	1	3	1	6
	6.2.2.1	Examine monitoring criteria, critical impact factors, and adaptive management of reefs	1	1	3	2	7
6.3 Dredged Channel Shallowing Research Agenda	6.3.1.1	Search potential channel shallowing site and conduct numerical studies	1	3	1	3	8
	6.3.1.2	Develop methods for valuing flood reductions	1	3	1	3	8
	6.3.2.1	Develop numerical models for circulation and transport	1	3	1	3	8
	6.3.2.2	Quantify the integrity of the restored habitats at a specific location	0	1	1	3	5
6.4 Ecologically-enhanced Bulkheads and Revetments Research Agendas	6.4.1	Define and standardize design rules for ecological enhancement	1	3	3	2	9
	6.4.2	Structural Benefits of Marine Growth on Marine Infrastructure	1	3	3	2	9

Agenda	Task	Brief Description	Prioritization				
			Fundamental principles	Chronology	Regional Applicability	Affordability	Overall weight
6.5 Living Shoreline Research Agendas	6.5.1.1	Develop a protocol for the monitoring and assessment of living shorelines	1	2	3	3	9
	6.5.1.2	Define and standardize design guidelines for living shorelines	1	3	3	3	10
	6.5.1.3	Evaluate the wave and current energy dissipation provided by various edge types using physical models and field studies	1	0	3	1	5

8. Literature Cited

Adams, D.A., J.S. O'Connor, and S.B. Weisberg. 1998. Final report: Sediment quality of the NY/NY harbor system. An Investigation under the Regional Environmental Monitoring and Assessment Program (R-EMAP). USEPA.

Adams, D., and S. Benyi. 2003. Sediment quality of the NY/NJ harbor system: A 5-year revisit (1993/4-1998). An Investigation under the Regional Environmental Monitoring and Assessment Program, Estuarine Program Agency.

Allen, H.H. 1978. Role of wetland plants in erosion control of riparian shorelines. Proceedings of the National Symposium on Wetlands, American Water Resources Association.

Allen, H.H., and J.R. Leech. 1997. Bioengineering guidelines for streambank erosion control. Environmental Impact Research Program Technical Report EL-97-8. U.S. Army Corps of Engineers Waterways Experiment Station. Vicksburg, MS.

Anderson, M.E., J.M. Smith, and S.K. McKay. 2011. Wave dissipation by vegetation. USACE. CHETN-I-82:

Anderson, M.G. 2008. Conserving Forest Ecosystems: Guidelines for Size, Condition and Landscape Requirements, in R. A. Askins, G. D. Dreyer, G. R. Visgilio and D. M. Whitelaw (eds.), Saving Biological Diversity: Balancing Protection of Endangered Species and Ecosystems, pp. 119-136. Springer-Verlag, New York, New York.

Aretxabaleta, A.L., B. Butman, and N.K. Ganju. 2014. Water level response in back-barrier bays unchanged following Hurricane Sandy, Geophysical Research Letters, 41(9), 2014GL059957.

Art, H.W. 1976. Ecological Studies of Sunken Forest, Fire Island National Seashore. NPS Scientific Monograph No. 7. NE Regional Office. Boston, Ma. Qk177.A75574.5' 264

Augustin, L.N. 2007. Laboratory experiments and numerical modeling of wave attenuation through artificial vegetation. Ocean Engineering, Texas A&M University. Master of Science: 106.

Augustin, L.N., J.L. Irish, G. Balsmeier, and J. Kaihatu. 2008. Laboratory measurements of wave attenuation and wave setup by vegetation. International Conference on Coastal Engineering, Hamburg, Germany, World Scientific.

Augustin, L.N., J.L. Irish, and P. Lynett. 2009. Laboratory and numerical studies of wave damping by emergent and near-emergent wetland vegetation, Coastal Engineering, 56, 332-340.

Baggett, L.P., S.P. Powers, R. Brumbaugh, L.D. Coen, B. DeAngelis, J. Greene, B. Hancock, and S. Morlock. 2014. Oyster habitat restoration monitoring and assessment handbook. The Nature Conservancy, Arlington, VA, USA., 96pp

Bain, M., J. Lodge, D.J. Suszkowski, D. Botkin, R. Diaz, K. Farley, J.S. Levinton, F. Steimle and P. Wilber. 2007. Target Ecosystem Characteristics for the Hudson Raritan Estuary: Technical Guidance for Developing a Comprehensive Ecosystem Restoration Plan. A report to the Port Authority of NY/NJ. Hudson River Foundation, New York, NY. 106 pp.

Barbier, E.B. 2013. Valuing ecosystem services for coastal wetland protection and restoration: Progress and challenges, Resources, 2(3), 213-230.

Barbier E.B., I.Y. Georgiou, B. Enchelmeyer, and D.J. Reed. 2013. The value of wetlands in protecting southeast Louisiana from hurricane storm surges. PLoS ONE 8(3): e58715. doi:10.1371/journal.pone.0058715

Barbier, E. B. and B. S. Enchelmeyer. 2014. Valuing the storm surge protection service of us gulf coast wetlands, Journal of Environmental Economics and Policy, 3(2), 167-185.

Belcher, S. E., N. Jerram and J. C. R. Hunt. 2003. Adjustment of a turbulent boundary layer to a canopy of roughness elements, Journal of Fluid Mechanics, 488, 369-398.

Bell, Robin Bell, W. Ryan, S. Carbotte, F. Nitsche, C. McHugh and L. Earth. 2005. Hudson River Estuary Sediment Cores Map (NYSDEC). http://gis.ny.gov/gisdata/metadata/nysdec.hre_SedimentCores.shp.xml. *Last accessed on 11/7/2014.*

Benavente, J., L.D. Rıó, F.J. Gracia, and J.A. Martıńez-del-Pozo. 2006. Coastal flooding hazard related to storms and coastal evolution in valdelagrana spit (cadiz bay natural park, sw spain), Continental Shelf Research, 26, 1061-1076.

Bradley, K., and C. Houser. 2009. Relative velocity of seagrass blades: Implications for wave attenuation in low energy environments, Journal of Geophysical Research, 114, F01004.Brandle, J.R., I. Hodges, and B. Wight. 2000. Windbreak practices. In: H.E. Garrett, W.J. Reitveld & R.F. Fisher, eds. North American agroforestry: an integrated science and practice. Madison, WI, American Society of Agronomy, Inc. 402 pp.

Bridges, T., R. Henn, S. Komlos, D. Scerno, T. Wamsley, and K. White. 2013. Coastal risk reduction and resilience: Using the full array of measures. Civil Work Technical Series. U.S. Army Corps of Engineers. http://www.corpsclimate.us/docs/USACE_Coastal_Risk_Reduction_final_CWTS_2013-3.pdf

Brumbaugh, R.D., M.W. Beck, L.D. Coen, L. Craig, and P. Hicks. 2006. A Practitioners' Guide to the Design and Monitoring of Shellfish Restoration Projects: An Ecosystem Services Approach. The Nature Conservancy, Arlington, VA.

Bunya, S., J.C. Dietrich, J.J. Westerink, B.A. Ebersole, J.M. Smith, J.H. Atkinson, R. Jensen, D.T. Resio, R.A. Luettich, C. Dawson, V.J. Cardone, A.T. Cox, M.D. Powell, H.J. Westerink, and H.J. Roberts. 2010. A high-resolution coupled riverine flow, tide, wind, wind waves, and storm surge model for southern Louisiana and Mississippi. Part i: Model development and validation, Monthly Weather Review, 138(2), 345-377.

Buzan, David, Wen Lee, Jan Culbertson, Nathun Kuhn, and Lance Robinson. 2009. Positive Relationship between Freshwater Inflow and Oyster Abundance in Galveston Bay, Texas. Estuaries and Coasts. 32:206-212.

Carollo, F. G., Ferro, V. and Termini, D. (2005). "Flow resistance law in channels with flexible submerged vegetation." Journal of Hydraulic Engineering 131(7), 554-564.

Carbotte, S., R. Bell, W. Ryan, C. McHugh, A.L. Slagle, F. Nitsche, and J. Rubenstone. 2004. Environmental change and oyster colonization within the Hudson River estuary linked to Holocene climate. Geo-Marine Letters 24:212-224.

Chen, Q., and H. Zhao. 2008. Hydrodynamic modeling of St. Joseph bay for stability analysis of coastal barrier breaching, Journal of Coastal Research 10.2112/1551-5036-52.sp1.181, 181-192.

Chen, Q., and H. Zhao. 2012. Theoretical model studies of wave energy dissipation due to vegetation, Journal of Engineering Mechanics, 138(2), 221-229.

Chin-Sweeney, P. 2003. Causes of historical oyster degradation in the Lower Hudson Estuary. Department of Earth and Environmental Science. Barnard College, Columbia College, New York, NY.

CBF 2007. Chesapeake Bay Foundation: Living Shorelines. http://www.cbf.org/Document.Doc?id=60. *Last accessed on 11/7/2014.*

Costanza, R., O. Pérez-Maqueo, M.L. Martinez, P. Sutton, S.J. Anderson, and K. Mulder. 2008. The value of coastal wetlands for hurricane protection, Ambio., 37(4), 241-248.

Costanza, R., M. Wilson, A. Troy, A. Voinov, S. Liu, and J. D'Agostino. 2006. The value of New Jersey's Ecosystem Services and Natural Capital. New Jersey Department of Environmental Protection, Trenton, NJ.

Czlapinski, R. 2013. Nature-based breakwater islands for the Fort Pierce marina: Planning and Design for Resiliency, Reliability, Acceptability, and Sustainability.

Dale, V.H., L.A. Joyce, S. McNulty, R.P. Neilson, M.P. Ayres, M.D. Flannigan, P.J. Hanson, L.C. Irland, A.E. Lugo, C.J. Pertson, D. Simberlogg, F.J. Swanson, B.J. Stocks, and B.M. Wotton. 2001. Climate Change and Forest Disturbance. BioScience. September. Vol. 51, No. 9:723-734. Online: http://ir.library.oregonstate.edu/xmlui/bitstream/handle/1957/17230/Climate%20change%20and%20forest%20disturbances.pdf?sequence=1

Davis, Jana L.D., Richard L. Takacs, and Robert Schnabel. 2006. Evaluating ecological impacts of living shorelines and shoreline habitat elements: an example from the upper western Chesapeake Bay. Management, Policy, Science, and Engineering of Nonstructural Erosion Control in the Chesapeake Bay. pp. 55-61.

Day, J. W. J., D. F. Boesch, E. J. Clairain, G. P. Kemp, S. B. Laska, W. J. Mitsch, K. Orth, H. Mashriqui, D. J. Reed, L. Shabman, C. A. Simenstad, B. J. Streever, R. R. Twilley, C. C. Watson, J. T. Wells and D. F. Whigham. 2007. Restoration of the mississippi delta: Lessons from hurricanes katrina and rita, Science, 315(5819), 1679-1684.

de Groot, R., L. Brander, S. van der Ploeg, R. Costanza, F. Bernard, L. Braat, M. Christie, N. Crossman, A. Ghermandi, L. Hein, et al. 2012. Global estimates of the value of ecosystems and their services in monetary units. Ecosystem Services, 1, 50-61.

De Vriend, H.J., and M. Van Koningsveld. 2012. Building with nature: Thinking, acting and interacting differently. EcoShape, Building with Nature, Dordrecht, the Netherlands.

Deegan, L.A., D.S. Johnson, R.S. Warren, B.J. Peterson, J.W. Fleeger, S. Fagherazzi, and W.M. Wollheim. 2012. Coastal eutrophication as a driver of salt marsh loss. Nature 400, 388-392.

Dietrich, J. C., J. J. Westerink, A. B. Kennedy, J. M. Smith, R. E. Jensen, M. Zijlema, L. H. Holthuijsen, C. Dawson, R. A. Luettich, M. D. Powell, V. J. Cardone, A. T. Cox, G. W. Stone, H. Pourtaheri, M. E. Hope, S. Tanaka, L. G. Westerink, H. J. Westerink and Z. Cobell. 2011. Hurricane Gustav

(2008) waves and storm surge: Hindcast, synoptic analysis, and validation in southern louisiana, Monthly Weather Review, 139(8), 2488-2522.

DRERIP, 2010. DRERIP Conceptual Models. https://www.dfg.ca.gov/erp/conceptual_models.asp. *Last accessed on 11/7/2014.*

Edinger, G.J., D.J. Evans, S. Gebauer, T.G. Howard, D.M. Hunt, and A.M. Olivero (editors). 2014. Ecological Communities of New York State. Second Edition. A revised and expanded edition of Carol Reschke's Ecological Communities of New York State. New York Natural Heritage Program, New York State Department of Environmental Conservation, Albany, NY.

Elwany, M.H.S., W.C. O'Reilly, R.T. Guza, and R.E. Flick. 1994. Effects of southern California kelp beds on waves, Journal of Waterway, Port, Coastal and Ocean Engineering, ASCE, 121(2), 143-150.

Ewart, J. W., and S. E. Ford. 1993. History and Impact of MSX and Dermo diseases on oyster stocks in the northeast region. Northeast Regional Aquaculture Center Factsheet No. 200. University of Massachusetts, North Dartmouth, Massachusetts.

Faber-Langendoen, D., J. Rocchio, M. Schafale, C. Nordman, M. Pyne, J. Teague, T. Foti, and P. Comer. 2006. Ecological Integrity Assessment and Performance Measures for Wetland Mitigation. NatureServe, Arlington, Virginia.

Fagherazzi, S., G. Mariotti, P.L. Wiberg, and K.J. McGlathery. 2013. Marsh collapse does not require sea level rise. Oceanography 26(3):70–77, http://dx.doi.org/10.5670/oceanog.2013.47

Feagin, R.A., N. Mukherjee, K. Shanker, A.H. Baird, J. Cinner, A.M. Kerr, N. Koedam, A. Sridhar, R. Arthur, L.P. Jayatissa, D.L. Seen, M. Menon, S. Rodriguez, M. Shamsuddoha, and F. Dahdouh-Guebas. 2010. Shelter from the storm? Use and misuse of coastal vegetation bioshields for managing natural disasters, Conservation Letters, 3, 1-11.

Fikes, R. 2013. Artificial reefs of the Gulf of Mexico: A review of gulf state programs & key considerations, National Wildlife Federation: 22.

Firth, L., M. Schofield, F.J. White, M. W. Skov, and S. J. Hawkins. 2014. Biodiversity in intertidal rock pools: Informing engineering criteria for artificial habitat enhancement in the built environment. Marine Environmental Research.

Fitzpatrick, P., Y. Lau, Y. Li, N. Tran, C. Hill, and S. Shean. 2009. Wetland attenuation of Hurricane Rita's storm surge. 2009 Northern Gulf Institute Annual Conference. Mobile, AL. PPT.

Freiwald, J., C. Wisniewski, M. Wehrenberg, C.S. Shuman, and C. Dawson. 2013. Reef Check California Instruction Manual: A Guide to Rocky Reef Monitoring, 7th Edition. Reef Check Foundation, Pacific Palisades, CA, USA.

Fritz, H.M., and C. Blount. 2007. Role of forests and trees in protecting coastal areas against cyclones. Coastal protection in the aftermath of the indian ocean tsunami: What role for forests and trees? S. Braatz, S. Fortuna, J. Broadhead and R. Leslie: 37-60.

Galtsoff, P. 1964. The American oyster Crassostrea virginica. US Fisheries Bulletin, pp. 1-480.

Gedan, K.B., M.L. Kirwan, E. Wolanski, E.B. Barbier, and B.R. Silliman. 2011. The present and future role of coastal wetland vegetation in protecting shorelines: Answering recent challenges to the paradigm, Climatic Change, 106, 7-29.

Georgetown Climate Center. 2013. Promoting Living Shorelines: Barriers and Opportunities presented by the Clean Water Act. Accessible at http://www.georgetownclimate.org/promoting-living-shorelines-barriers-and-opportunities-presented-by-the-clean-water-act Pre-publication draft, November 2013.

Grabowski, J.H., A.R. Hughes, D.L. Kimbro, and M.A. Dolan. 2005. How habitat setting influences restored oyster reef communities. Ecology 86:1926-1935.

Grabowski, J.H., R.D. Brumbaugh, R.F. Conrad, A.G. Keeler, J.J. Opaluch, C.H. Peterson, M.F. Piehler, S.P. Powers, and A.R. Smyth. 2012. Economic valuation of ecosystem services provided by oyster reefs, BioScience, 62(10), 900-909.

Gray, D.H. 1977. The influence of vegetation on slope processes in the Great Lakes Region. Proceedings: Workshop on the role of vegetation in stabilization of the Great Lakes Shoreline. Great Lakes Basin Commission, Ann Arbor, MI.

Groves, Craig R, Edward T. Game, Mark G. Anderson, Molly Cross, Carolyn Enquist, Zach Ferdaña, Evan Girvetz, Anne Gondor, Kimberly R. Hall, Jonathan Higgins, Rob Marshall, Ken Popper, Steve Schill, and Sarah L. Shafer. 2012. Incorporating climate change into systematic conservation planning. Biodiversity and Conservation. Online: http://www.esajournals.org/doi/abs/10.1890/06-1115.1

Grzegorzewski, A.S., M. Cialone, and T. Wamsley. 2011. Interaction of barrier islands and storms: Implications for flood risk reduction in Louisiana and Mississippi, Journal of Coastal Research (SI), 59, 156-164.

Grzegorzewski, A.S., M. Cialone, A.J. Lansen, M. van Ledden, J.M. Smith and T.V. Wamsley. 2008. The influence of barrier islands on hurricane-generated storm surge and waves in Louisiana and Mississippi. Proceedings of the 31st International Conference on Coastal Engineering, Hamburg, Germany.

Gross, John E. 2003. Developing Conceptual Models for Monitoring Programs. NPS Inventory and Monitoring Program, http://science.nature.nps.gov/im/monitor/docs/Conceptual_modelling.pdf

Guise, A.M. 2014. North Atlantic coast comprehensive study: Resilient adaption to increasing risk, U.S. Army Corps of Engineers Coastal Storm Risk Management Planning Center of Expertise. http://www.nad.usace.army.mil/Portals/40/docs/ComprehensiveStudy/Nov_13/Guise_NACCS_overview.pdf. Accessed 09/2014.

Hardaway, Jr., C. Scott, and James R. Gunn. 2010. Design and performance of headland bays in Chesapeake Bay, USA. Coastal Engineering. 57(2):203–212

Hartig, E.K., F. Mushacke, D. Fallon, A. Kolker, and V. Gornitz. 2002. Anthropogenic and climate-change impacts on salt marshes of Jamaica Bay, New York City. Wetlands 22, 71-89.

Hauser, E. 2012. Terminology for the Hudson River Sustainable Shorelines Project. In association with and published by the Hudson River Sustainable Shorelines Project, Staatsburg, NY 12580, Http://hrnerr.org

Herrington, T.O., R. Datla, and R. Royce. 2005. Alternative Shoreline Stabilization Structures: Physical Model Tests. Davidson Laboratory, TR SIT-04090284.

Holland, G. 2008. A revised hurricane pressure–wind model, Monthly Weather Review, 136(9), 3432-3445.

IADNR. 2006. How to Control Streambank Erosion. http://www.ctre.iastate.edu/erosion/manuals/streambank_erosion.pdf

Irish, J L., L.N. Augustin, G.E. Balsmeier, and J.M. Kaihatu. 2008. Wave dynamics in coastal wetlands: A state-of-knowledge review with emphasis on wetland functionality for storm damage reduction, Shore and Beach, 76(3), 52-56.

Jones, K., H. Feng, S. Yoon, and A. Lanzirotti. 2002. Metal Distributions in NY/NJ Waterway Sediment using Fluorescence Computed Microtomography. X26A. Abstract No. Jone0513. In: National

Synchrotron Light Source Activity Report 2002. Brookhaven National Laboratory, Upton, New York.

Karen A. Poiani, Brian D. Richter, Mark G. Anderson and Holly E. Richter. 2000. Biodiversity Conservation at Multiple Scales: Functional Sites, Landscapes, and Networks. BioScience 50 (2): 133-146. doi: 10.1641/0006-3568(2000)050[0133:BCAMSF]2.3.C Online: http://bioscience.oxfordjournals.org/content/50/2/133.full

Kennedy, A.B., U. Gravois, B. Zachry, R. Luettich, T. Whipple, R. Weaver, J. Reynolds-Fleming, Q. Chen, and R. Avissar. 2010. Rapidly installed temporary gauging for waves and surge, and application to Hurricane Gustav. Cont. Shelf Res., 30, 1743-1752.

Kennedy, A.B., U. Gravois, B.C. Zachry, J.J. Westerink, M.E. Hope, J.C. Dietrich, M.D. Powell, A.T. Cox, R.L. Luettich, and R.G. Dean. 2011. Origin of the Hurricane Ike forerunner surge. Geophys. Res. Lett. 38(8).

Klingeman, P.C., and J.B. Bradley. 1976. Willamette River Basin streambank stabilization by natural means. U.S. Army Engineer Portland District, Portland, OR.

Kirwan, M.L., and S.M. Mudd. 2012. Response of salt-marsh carbon accumulation to climate change. Nature 489:550–553.

Kirwan, M.L., G.R. Guntenspergen, A. D'Alpaos, J.T. Morris, S.M. Mudd, and S. Temmerman. 2010. Limits on the adaptability of coastal marshes to rising sea level: Geophysical Research Letters, v. 37.

Kiviat, E. 2013. Ecosystem services of Phragmites in North America with emphasis on habitat functions. AoB PLANTS 5: plt008; doi:10.1093/aobpla/plt008 Available here: http://aobpla.oxfordjournals.org/

Knutson, T.R., J.L. McBride, J. Chan, K. Emanuel, G. Holland, C. Landsea, I. Held, J. P. Kossin, A.K. Srivastava and M. Sugi. 2010. Tropical cyclones and climate change, Nature Geosci, 3(3), 157-163.

Koch, E.W., E.B. Barbier, B.R. Silliman, D.J. Reed, G.M.E. Perillo, S.D. Hacker, E.F. Granek, J.H. Primavera, N. Muthiga, S. Polasky, B.S. Halpern, C.J. Kennedy, C.V. Kappel, and E. Wolanski. 2009. Non-linearity in ecosystem services: Temporal and spatial variability in coastal protection, Frontiers in Ecology and the Environment, 7(1), 29-37.

Krauss, K. W., T. W. Doyle, T. J. Doyle, C. M. Swarzenski, A. S. From, R. H. Day and W. H. Conner. 2009. Water level observations in mangrove swamps during two hurricanes in florida, Wetlands, 29(1), 142-149.

Kreeger D., and J. Moody. 2014. A Framework for Standardized Monitoring of Living Shorelines in the Delaware Estuary and Beyond (Draft). April 22.

Kroeger, T. 2012. Dollars and sense: Economic benefits and impacts from two oyster reef restoration projects in the northern Gulf of Mexico. The Natural Conservancy.

Kusler, J.A. 1983. Our national wetland heritage-A protection guidebook: Washington, D. C., Environmental Law Institute, p. 4.

Kusler, Jon A., and Mary E. Kentula. 1989a. Wetland creation and restoration: the status of the science. Vol. 1 Regional Reviews. EPA1600/3-89/038A. U.S. Environmental Protection Agency, Environmental Research Laboratory, Corvallis, Oregon, USA.

Kusler, Jon A., and Mary E. Kentula 1989b. Wetland creation and restoration: the status of the science. Vol. 2 Perspectives. EPA1600/3-89/038. U.S. Environmental Protection Agency, Environmental Research Laboratory, Corvallis, Oregon, USA.

Lenihan, H.S. 1999. Physical-biological coupling on oyster reefs: how habitat structure influences individual performance. Ecological Monographs 69:251-275.

Li, C.W., and K. Yan. 2007. Numerical investigation of wave-current-vegetation interaction, Journal of Hydraulic Engineering, 133(7), 794-803.

Lima, S.F., C.F. Neves, and N.M.L. Rosauro. 2006. Damping of gravity waves by fields of flexible vegetation. International Conference on Coastal Engineering, San Diego, California, USA, World Scientific eBooks.

Lövstedt, C.B., and M. Larson. 2010. Wave damping in reed: Field measurements and mathematical modeling, Journal of Hydraulic Engineering, 136(4), 222-233.

Lowe, R.J., J.L. Falter, J.R. Koseff, S.G. Monismith, and M.J. Atkinson. 2007. Spectral wave flow attenuation within submerged canopies: Implications for wave energy dissipation, Journal of Geophysical Research, 112(C05018).

Luckenbach, M.W., and L. Coen. 2003. Oyster reef habitat restoration: ecological benefits, restoration approaches and an agenda for the future. Inaugural National Conference on Coastal and Estuarine Habitat Restoration, Baltimore, Maryland.

Luettich, Rick and Westerink, Joannes, 2010. ADCIRC: A (Parrallel) Advanced Circulation Model for Oceanic, Coastal and Estuarine Waters. A User's Manual. V.49, 4/1/2010. http://www.unc.edu/ims/adcirc/documentv49/ADCIRC_title_page.html. *Last accessed on 11/5/2014.*

Mariotti, G., and Fagherazzi, S., 2013, Critical width of tidal flats triggers marsh collapse in the absence of sea-level rise: Proceedings of the National Academy of Sciences, v. 110, p. 5353-5356.

Mazda, Y., M. Magi, Y. Ikeda, T. Kurokawa, and T. Asano. 2006. Wave reduction in a mangrove forest dominated by sonneratia sp., Wetlands Ecology and Management, 14, 365-378.

Meli, P., J.M.R. Benayas, P. Balvanera, and M.M. Ramos. 2014. Restoration enhances wetland biodiversity and ecosystem service supply, but results are context dependent: a meta-analysis. PLoS ONE, 9, 1-9.

Miller, J., A. Rella, and E. Hopson. 2014. Living Shorelines Engineering Guidelines, s.l.: Developed for NJDEP.

Miller, Robin E. Landeck, K.J. Farley, James R. Wands, Robert Santore, Aaron D. Redman, and Nicholas B. Kim. 2011. Fate and transport modeling of sediment contaminants in the New York/New Jersey harbor estuary, Urban Habitats, 6.

Morris, J. 2010. The limits of salt marsh adaptation to rising sea level. International Conference on Sea Level Rise in the Gulf of Mexico: Impacts, Adaptations, and Management. Corpus Christi, Texas.

Moseman-Valtierra, Serena. 2011. New CELS researcher part of salt marsh collaborative study. CELS News Editor. http://cels.uri.edu/news/nSerenagrant.aspx. Access 5/12/2014

NACCS. 2014. North Atlantic Coast Comprehensive Study.

Neckles, H.A., G.R. Guntenspergen, W.G. Shriver, N.P. Danz, W.A. Wiest, J.L. Nagel, and J.H. Olker. 2013. Identification of Metrics to Monitor Salt Marsh Integrity on National Wildlife Refuges In Relation to Conservation and Management Objectives. Final Report to U.S. Fish and Wildlife Service, Northeast Region. USGS Patuxent Wildlife Research Center, Laurel, MD. 226 pp.

Nepf, H.M. and E.R. Vivoni. 2000. Flow structure in depth-limited, vegetated flow, Journal of Geophysical Research, 105(C12), 28547-28557.

Neumeier, U., and C.L. Amos. 2006. The influence of vegetation on turbulence and flow velocities in European salt-marshes, Sedimentology, 53(2), 259-277.

Newell, R.I., and E.W. Koch. 2004. Modeling seagrass density and distribution in response to changes in turbidity stemming from bivalve filtration and seagrass sediment stabilization. Estuaries 27:793-806.

Nikora, V., D. Goring, I. McEwan, and G. Griffiths. 2001. Spatially averaged open-channel flow over rough bed., Journal of Hydraulic Engineering, 127(2), 123-133.

NPCC. 2014. Climate Risk Information 2014, New York City Panel on Climate Change, in press.

NY/NJ Baykeeper. 2005. Oyster Gardening Program Manual, Keyport, New Jersey: Raritan Baykeeper, Inc.

NY/NJ Baykeeper. 2006. Baykeeper Volunteer Oyster Restoration Program Achieves Historic Milestone. Estuarian.

NY/NJ HEP. 2008. Regional sediment management plan. http://www.harborestuary.org/reports/Reg_Sed_Mgmnt_Plan0908.pdf. *Last accessed on 11/7/2014.*

NY/NJ HEP. 2012. The State of the Estuary 2012. New York-New Jersey Harbor and Estuary Program.

NYC DCP. 1982. Waterfront Revitalization Program (WRP). http://www.nyc.gov/html/dcp/html/wrp/wrp_1.shtml. Accessed 09/2014

NYC DCP. 2002. Waterfront Revitalization Program (WRP). http://www.nyc.gov/html/dcp/html/wrp/wrp_1.shtml. Accessed 09/2014

NYC DCP. 2011. Vision 2020: New York City Comprehensive waterfront plan. Collaboration of The City of New York and Department of City Planning.

NYC DCP. 2013. Coastal Climate Resilience: Urban Waterfront Adaptive Strategies. Collaboration of The City of New York and Department of City Planning.

MWA (Metropolitan Waterfront Alliance) . 2014. Waterfront Edge Design Guidelines. Ongoing program.

NYCDEP. 2008. New York Harbor Water Quality Report. http://www.nyc.gov/html/dep/pdf/hwqs2008.pdf. *Last accessed on 11/1/2014*

NYSDEC. 2013. Watchable wildlife: Shorebird festival at Jamaica Bay. DEC Outdoor Discovery. http://www.dec.ny.gov/public/92664.html.

Nyman, John A., Russel J. Walters, Ronald D. Delaune, William H. Patrick Jr. 2006. Marsh vertical accretion via vegetative growth. Estuarine, Coastal and Shelf Science 69 (2006) 370e380

Orton, P.M., et al. (in preparation), Wetland and bathymetry restoration as mitigation of storm tides and sea level rise, in preparation for Nature Climate Change.

Otten, C. J., P. Bakker and M. Meijer. 2006. Reduction of hurricane impact by re-creation of marshlands and barrier islands, Terra et Aqua(105), 20-31.

Orton, P.M., N. Georgas, and A. Blumberg. 2012. Contrasting NYC Coastal Restoration and Storm Surge Barrier Impacts on Flooding, paper presented at Abstract NH23C-08 presented at 2012 Fall Meeting, AGU, San Francisco, CA, 3-7 Dec.

Patil, S., and V.P. Singh. 2009. Hydrodynamics of wave and current vegetation interaction, Journal of Hydrologic Engineering, 14(12), 1320-1333.

Pendleton, L., P. Atiyah, and A. Moorthy. 2007. Is the non-market literature adequate to support coastal and marine management. Ocean Coast Management. 50, 363–378.

Perkol-Finkel, S., G. Zilman, I. Sella, T. Miloh, and Y. Benayahu. 2006. Floating and fixed artificial habitats: effects of substratum motion on benthic communities in a coral reef environment. Marine Ecology Progress Series, 18 July, pp. Vol. 317: 9-20.

Perkol-Finkel, Shimrit, and Ido Sella. 2013. Ecologically Active Concrete for Coastal and Marine Infrastructures: Innovative Matrices and Designs, Tel Aviv, Israel: ECOncrete Tech, LTD..

Peyronnin, N., M. Green, C. P. Richards, A. Owens, D. Reed, J. Chamberlain, D. G. Groves, W. K. Rhinehart and K. Belhadjali. 2013. Louisiana's 2012 coastal master plan: Overview of a science-based and publicly informed decision-making process, Journal of Coastal Research 10.2112/si_67_1.1, 1-15.

Poiani, Karen A., Brian D. Richter, Mark G. Anderson, and Holly E. Richter. 2000. Biodiversity Conservation at Multiple Scales: Functional Sites, Landscapes, and Networks. BioScience 50 (2): 133-146. doi: 10.1641/0006-3568(2000)050[0133:BCAMSF]2.3.C Online: http://bioscience.oxfordjournals.org/content/50/2/133.full.

Powell, M. D., S. H.Houston, and T. A. Reinhold, 1996: Hurricane Andrew's Landfall in South Florida. Part I: Standardizing measurements for documentation of surface wind fields. Weather Forecast., 11, 304-328.

Ravit, B.Q.S.C.K. 2012. NY/NJ Baykeeper Oyster Habitat Restoration Feasibility Study, s.l.: Rutgers Center for Urban Environmental Sustainability.

Rego, J.L., and C. Li. 2010. Storm surge propagation in Galveston Bay during Hurricane Ike, Journal of Marine Systems, 82, 265-279.

Reid, J.M., J.A. Reid, C.J. Jenkins, M.E. Hastings, S.J. Williams, and L.J. Poppe. 2005, usSEABED: Atlantic coast offshore surficial sediment data release: U.S. Geological Survey Data Series 118, version 1.0. Online at http://pubs.usgs.gov/ds/2005/118/

Rella, A., and J.K. Miller. 2012. A Comparative Cost Analysis of Ten Shore Protection Methods at Three Sites Under Two Sea Level Rise Scenarios, s.l.: Hudson River Sustainable Shorelines Project.

Rella, A. 2014. Evaluating the Effectiveness of Downwellling Surface Water to Encourage the Development of Oyster Habitat in the Hudson-Raritan Estuary, Hoboken, NJ: Stevens Institute of Technology.

Risinger, J.D. 2012. Biologically Dominated Engineered Coastal Breakwaters, A Dissertation, s.l.: Louisiana State University, The Department of Biological and Agricultural Engineering.

Rosati, J.D. 2009. Concepts for functional restoration of barrier islands. U.S. Army Corps of Engineers. ERDC/CHL CHETN-IV-74.

Rosenberg, N.J. (1974). Microclimate : the biological environment. John wiley & Sons, New York.

Ruckelshaus, M., S.C. Doney, H.M. Galindo, J.P. Barry, F. Chane, J.E. Duffy, C.A. English, S.D. Gaines, J.M. Grebmeier, A.B. Hollowed, N. Knowlton, J. Polovina, N.N. Rabalais, W.J. Sydeman, and L.D. Talley. 2013. Securing ocean benefits for society in the face of climate change. Marine Policy, 40, 154–159. http://www.sciencedirect.com/science/article/pii/S0308597X13000183

Russell, Nicole, and Gary Griggs. 2012. Adapting to Sea Level Rise: A Guide for California's Coastal Communities. http://seymourcenter.ucsc.edu/OOB/Adapting%20to%20Sea%20Level%20Rise.pdf

Scyphers, S.B., S.P. Powers, K.L. Heck, Jr., and D. Byron. 2011. Oyster Reefs as Natural Breakwaters Mitigate Shoreline Loss and Facilitate Fisheries. PLoS ONE 6(8): e22396. doi:10.1371/journal.pone.0022396

Shaffer, G.P., J.W.J. Day, S. Mack, G.P. Kemp, I. van Heerden, M.A. Poirrier, K.A. Westphal, D.M. FitzGerald, A. Milance, C.A. Morris, R. Bea, and P.S. Penland. 2009. The MRGO navigation project: A massive human-induced environmental, economic, and storm disaster, Journal of Coastal Research (SI), 54, 206-224.

Shepard, C.C., C.M. Crain, and M.W. Beck. 2011. The protective role of coastal marshes: A systematic review and meta-analysis, PLoS ONE, 6(11).

Skidmore, E.L. (1986). Wind erosion control. Climatic Change, 9, 209-218.

Smith, C. R., S. D. DeGloria. M. E. Richmond, S. K. Gregory, M. Laba, S. D. Smith, J. L. Braden, E. H. Fegraus, E. A Hill, D. E. Ogurcak, and J.T. Weber. 2001. The New York GAP Analysis Project Final Report. New York Cooperative Fish and Wildlife Research Unit, Department of Natural Resources, Cornell University, Ithaca, N.Y. 134 p., append.

Smith, Stephen D., Warren A. Brown, Charles R. Smith, and Milo E. Richmond. 2002. Habitat Vulnerability Assessment in the Hudson River Valley. USGS GAP Analysis Bulletin 13.

Sotir, R.B., and J.C. Fischenich. 2007. Live Stake and Joint Planting for Streambank Erosion Control. EMRRP Technical Notes Collection (ERDC TN-EMRRP-SR-35), U.S. Army Engineer Research and Development Center, Vicksburg, MS.

Spalding, M.D., A.L. McIvor, M.W. Beck, E.W. Koch, I. Möller, D.J. Reed, P. Rubinoff, T. Spencer, T.J. Tolhurst, T.V. Wamsley, B.K. van Wesenbeeck, E. Wolanski and C.D. Woodroffe. 2013. Coastal ecosystems: A critical element of risk reduction, Conservation Letters, 7(3), 293-301.

Spalding, Mark D., Susan Ruffob, Carmen Lacambrac, Imèn Melianeb, Lynne Zeitlin Haleb, Christine C. Shepardd, and Michael W. Beck. 2014. The role of ecosystems in coastal protection: Adapting to climate change and coastal hazards. Ocean & Coastal Management, 90, 50–57. http://www.sciencedirect.com/science/article/pii/S0964569113002147

Steimle, F. 2005. Natural oyster reef habitat in the Hudson-Raritan Estuary. Oyster restoration in the Hudson-Raritan Estuary: What are the challenges? What are the solutions? Monmouth University, West Long Branch, NJ. Raritan Baykeeper, Inc., Keyport, NJ.

Stern, E.A., K.W. Jones, W.S. Douglas, H. Feng, N.L. Clesceri, and J.L. Lodge. 2002. Sediment decontamination with beneficial use for the Port of New York and New Jersey (abstract). Presented at USEPA Science Forum 2002, Washington, DC, May 1-2, 2002. (BNL-69253).

Stern, E.A., K.W. Jones, W.S. Douglas, H. Feng, and Stefano Della Sala. 2005. Full Scale Sediment decontamination Applications – New York/New Jersey Harbor. Abstract of talk to be presented at the International Conference on Remediation of Contaminated Sediment. January 24-27, 2005. New Orleans, Louisiana.

Steyer, G.D., R.R. Twilley, and R.C. Raynie. 2006. An Integrated Monitoring Approach Using Multiple Reference Sites to Assess Sustainable Restoration in Coastal Louisiana. Pages 326 – 333 In Aguirre-Bravo, C., Pellicane, Patrick J., Burns, Denver P., and Draggan, Sidney (Eds.) Monitoring Science and Technology Symposium: Unifying Knowledge for Sustainability in the Western Hemisphere. 2004 September 20-24, Denver, CO. Proceedings RMRS-P-42CD, Fort Collins, CO, U.S. Department of Agriculture, Forest Service, Rocky Mountain Research Station. 990 p.

Steyer, G.D., C.E. Sasser, J.M. Visser, E.M. Swensen, J.A. Nyman, and R.C. Raynie. 2003. A proposed coast-wide refer-ence monitoring system for evaluating wetland restoration trajectories in Louisiana: Environmental Monitoring and Assessment, v. 81, p. 107–117.

Stone, B. M. and H. T. Shen. 2002. Hydraulic resistance of flow in channels with cylindrical roughness, Journal of Hydraulic Engineering, 128(5), 500-506.

Stone, G. W., X. Zhang and A. Sheremet. 2005. The role of barrier islands, muddy shelf and reefs in mitigating the wave field along coast louisiana, Journal of Coastal Research (SI), 44, 40-55.

Strayer, David L. 2007. Submersed vegetation as habitat for invertebrates in the Hudson River estuary. Estuaries and Coasts 30.2: 253-264.

Strayer, David L., and Lane C. Smith. 2000. Macroinvertebrates of a rocky shore in the freshwater tidal Hudson River. Estuaries 23.3: 359-366.

Suzuki, T., J. Dijkstra, and M.J.F. Stive. 2008. Wave dissipation on a vegetated salt marsh. International Conference on Coastal Engineering, Hamburg, Germany, World Scientific.

Swann, L. 2008. The use of living shorelines to mitigate the effects of storm events on Dauphin Island, Alabama, USA. Am Fish Soc Symp 64:47–57

Swanson, R.L. and R.E. Wilson. 2006. Increased Tidal Ranges Coinciding with Jamaica Bay Development Contribute to Marsh Flooding. Journal of Coastal Research 24(6), 1565-1569.

Swanson, R.L., and R.E. Wilson. 2008. Increased Tidal Ranges Coinciding with Jamaica Bay Development Contribute to Marsh Flooding, Journal of Coastal Research, 1565-1569.

Swanson, R.L. A.S. West-Valle, and C.J. Decker. 1992. Recreation vs. waste disposal: The use and management of Jamaica Bay. Long Island Historical Journal, 5(1), 21–41.

Taylor, J. and D. Bushek 2008. Intertidal oyster reefs can persist and function in a temperate north american atlantic estuary, Marine Ecology Progress Series, 361, 301-306.

Tanino, Y., and H.M. Nepf. 2008. Laboratory investigation of mean drag in a random array of rigid, emergent cylinders, Journal of Hydraulic Engineering, 134(1), 34-41.

The City of New York. 2011. PlaNYC: A greener, greater New York. Mayor M. R. Bloomberg

The City of New York. 2013. Special Initiative for Rebuilding and Resiliency: A stronger, more resilient New York. Mayor M. R. Bloomberg

TNC. 2011. Living Shoreline and Oyster Reef Restoration, Pensacola, FL. http://www.dep.state.fl.us/deepwaterhorizon/files2/projects/mutiple/m8_shorelines_oyster_reef_restoration.pdf

TNC. 2012. Living shoreline project: Altamaha-Ogeechee estuarine complex, GA. Alternative estuarine erosion control and implementation, The Natural Conservancy.

TNC. 2013. Integrating natural infrastructure into urban coastal resilience Howard Beach, Queens. December 2013. http://www.nature.org/ourinitiatives/regions/northamerica/unitedstates/newyork/natural-infrastructure-study-at-howard-beach.xml

USACE. 1963. Overland surge elevations coastal Louisiana: Morgan city and vicinity. File No. H-2-22758: Plate A-4.

USACE. 1984. Shore Protection Manual: Volumes I and II. Coastal Engineering Research Center, Vicksburg, MS.

USACE. 2002. Coastal Engineering Manual. Coastal and Hydraulics Laboratory, Engineer Research and Development Center, Vicksburg, MD.

USACE and NY/NJ Port Authority. 2009. Hudson Raritan Estuary Comprehensive Restoration Plan (Draft). March.

USEPA. 1991. Research Plan for Monitoring Wetland Ecosystems. (Authors: N.C. Leibowitz, L. Squires, and J.P. Baker. EPA/600/3-91-010. April. Online: http://nepis.epa.gov/Exe/ZyPDF.cgi/2000IEED.PDF?Dockey=2000IEED.PDF

Valdemoro, Herminia I., Agustín Sánchez-Arcilla, José A. Jiménez. 2007. Coastal dynamics and wetlands stability: The Ebro delta case. Hydrobiologia, 577 (1), pp 17-29. http://link.springer.com/article/10.1007%2Fs10750-006-0414-7

van Slobbe, E., H. J. de Vriend, S. Aarninkhof, K. Lulofs, M. de Vries and P. Dircke. 2013. Building with nature: In search of resilient storm surge protection strategies, Natural Hazards, 66(3), 1461-1480.

Vickery, P., J. Lin, P. Skerlj, L. Twisdale and K. Huang. 2006. Hazus-mh hurricane model methodology. I: Hurricane hazard, terrain, and wind load modeling, Natural Hazards Review, 7(2), 82-93.

Wainger, L., S. Sifleet, D. Shafer, and S. Bourne. 2013. Ecosystem Service Benefits of USACE Ecological Restoration Projects in the Coastal Northeast: Hurricane Sandy Case Study. Draft Report (9/6/2013).

Wang, H., and E.S. Takle. 1996. On three-dimensionality of shelterbelt structure and its influences on shelter effects. Bound.-Layer Meteor., 79: 83–105.

Wells, H. 1961. The fauna of oyster beds, with special reference to the salinity factor. Ecological Monographs 31:239-266.

Whitaker, J. D., J. W. McCord, B. Pulley and E. H. Mullins (2009). Best management practices for wildlife in maritime forest developments.

Wigand et al. 2014. Preliminary research: chronically nitrogen enriched ecosystems carbon storage. In prep.

Wilson, C.A.M.E. 2007. Flow resistance models for flexible submerged vegetation, Journal of Hydrology, 342, 213-222.

Wilson, C.A.M.E., and M.S. Horritt. 2002. Measuring the flow resistance of submerged grass, Hydrological Processes, 16(13), 2589-2598.

Wu, F.-S., Shen, H. W. and Chou, Y.-J. (1999). “Variation of roughness coefficient for unsubmerged and submerged vegetation.” Journal of Hydraulic Engineering, 125(9) , 934-942.

Wu, Y., R.A. Falconer, and J. Struve. 2001. Mathematical modelling of tidal currents in mangrove forests, Environmental Modelling & Software, 16(1), 19-29.

Yang, S.L. 1998. The role of scirpus marsh in attenuation of hydrodynamics and retention of fine sediment in the Yangtze estuary, Estuarine, Coastal and Shelf Science, 47(2), 227-233.

Zarnoch et al. 2012. Growth and Reproduction of Eastern Oysters, Crassostrea Virginica, in a New York City Estuary: Implications for Restoration. Urban Habitats. March 2012. http://www.urbanhabitats.org/v07n01/easternoysters_full.html

Zhao, H. and Q. Chen. 2014. Modeling attenuation of storm surge over deformable vegetation: Methodology and verification, Journal of Engineering Mechanics, 0(0), 04014090.

zu Ermgassen, P.S.E., M.W. Gray, C.J. Langdon, M.D. Spalding, and R.D. Brumbaugh. 2013. Quantifying the historic contribution of olympia oysters to filtration in pacific coast (USA) estuaries and the implications for restoration objectives, Aquatic Ecology, 47(2), 149-161.